*Wednesday, April 15, 2026*

# Natural and anthropogenic sinkholes


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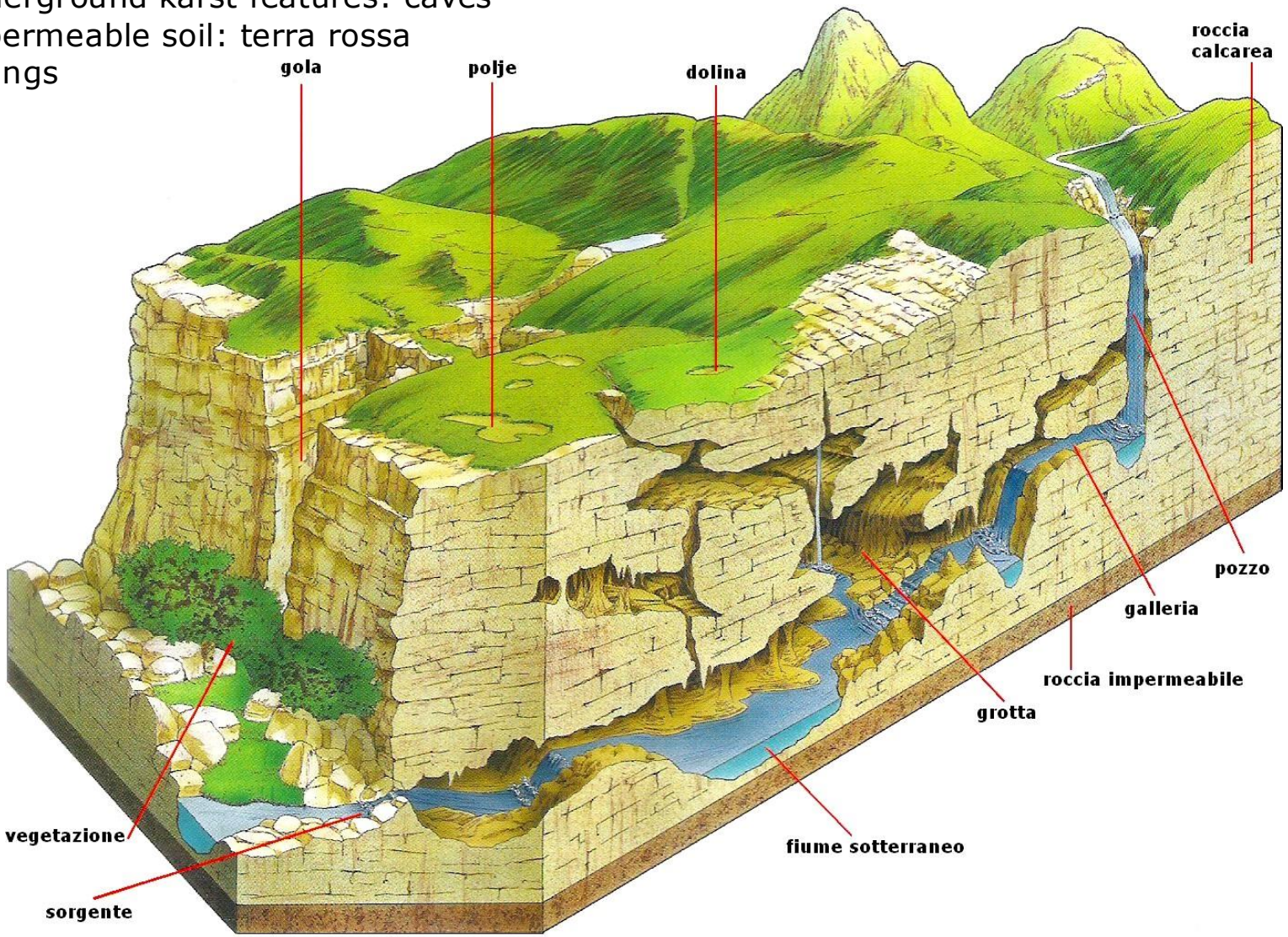
# Outline of the presentation

- Introduction to karst
- Sinkholes, and sinkhole classification
- Artificial cavities and anthropogenic sinkholes
- Sinkholes in non karst settings

# Main characters of karst landscape

- Absence of an epigean hydrographic network: rivers, streams, lakes...
- Presence of groundwater
- Presence of epigean karst features: karren, sinkholes, swallowholes
- Presence of underground karst features: caves
- Presence of impermeable soil: terra rossa
- Presence of springs



# What is karst ?

$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{++} + 2(HCO_3)^-$

DISSOLUTION
of Calcium Carbonate

$CaCO_3 + H_2O + CO_2 \leftarrow Ca^{++} + 2(HCO_3)^-$

CONCRECTION
of Calcium Carbonate

$CaCO_3$ **Calcium Carbonate - solid component**

$H_2O$ **Water , liquid component**

$CO_2$ **Carbon dioxide, gas component**

$Ca^{++}$ **CALCIUM Ion**

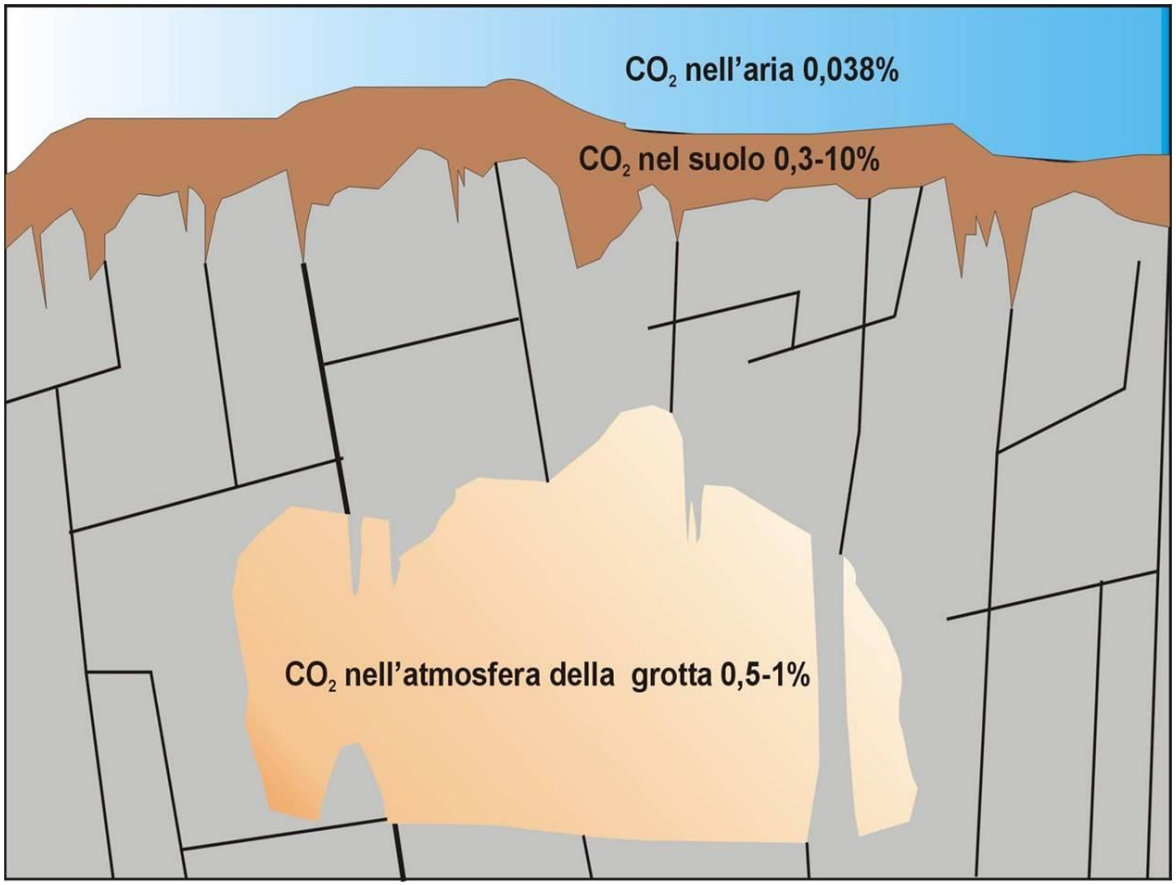
$2(HCO_3)^-$ **BICARBONATE ion**

**$CO_2$ the main actor in karst**

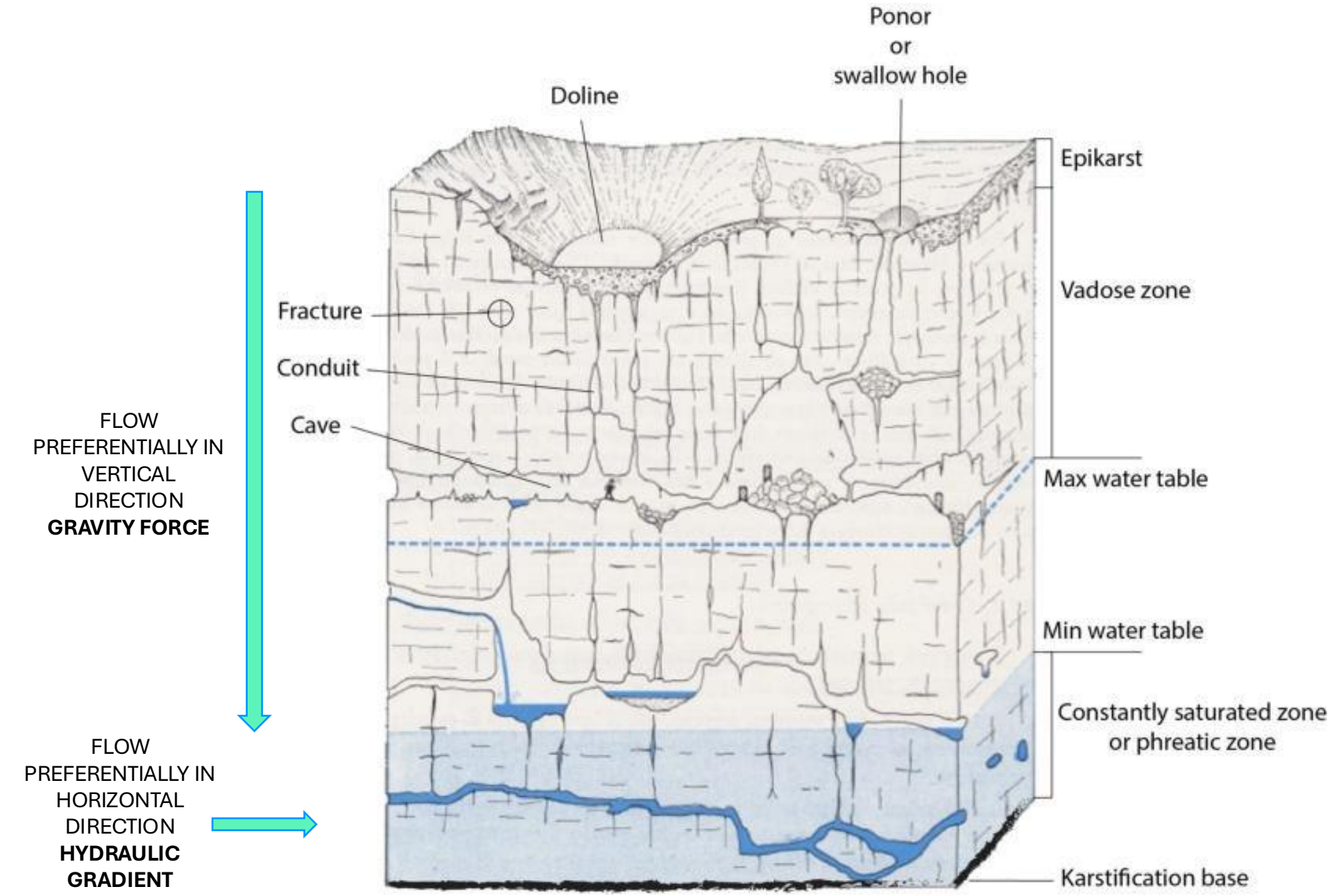
## Air
about 0,038%

## Soil
0,1-15%
(mean 0,3-10 %)

## Cave
0,5-1%
(2-20 times higher than the concentration of CO2 in the atmosphere!!).



# How water moves in karst terrain



# *SINKHOLES*

***Sinkhole:*** circular depression in karst.
It has underground drainage, size comprised between meters and tens of meters, and typically is in the shape of a funnel.

after Bates & Jackson, 1987, Glossary of Geology, 3rd edition

Florida (US NEWS & World Report)

Devil’s Sinkhole, Texas, USA

Bottomless Lakes State Park,
New Mexico, USA

## doline

from slavic language (*dol* = valley).
Superficial cavity, typical of karst regions, in approximately circular or oval shape, more or less wide (from a few decimeters in diameter to several hundreds of meters), with variable depth.

Term widely used in Europe (Classical Karst), also historically, with mostly geomorphological meaning

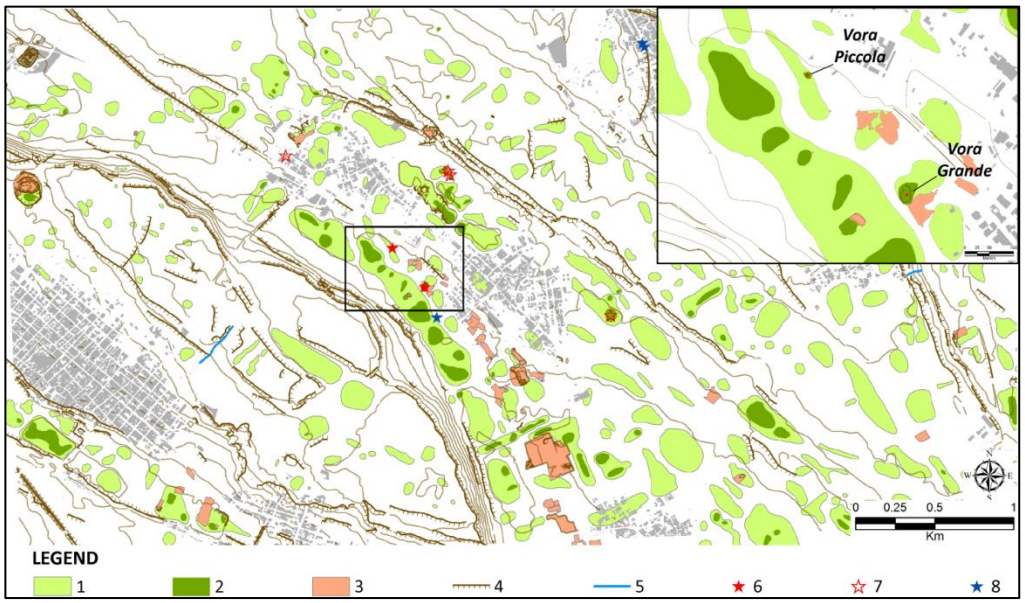
## *sinkhole*

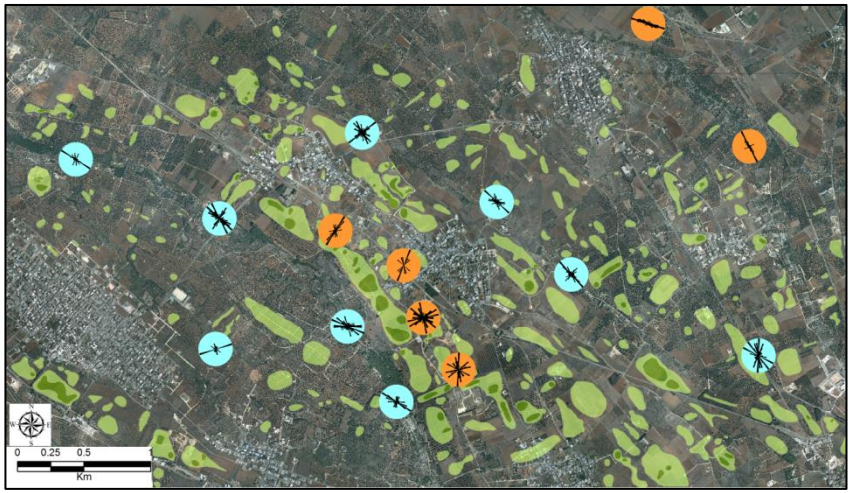
anglosaxon term, nowadays commonly used in many other countries, including Italy.
After the *Glossary of geology*: circular depression in karst environment; it presents underground drainage, size between meters and tens of meters, and typically is in the shape of a funnel.

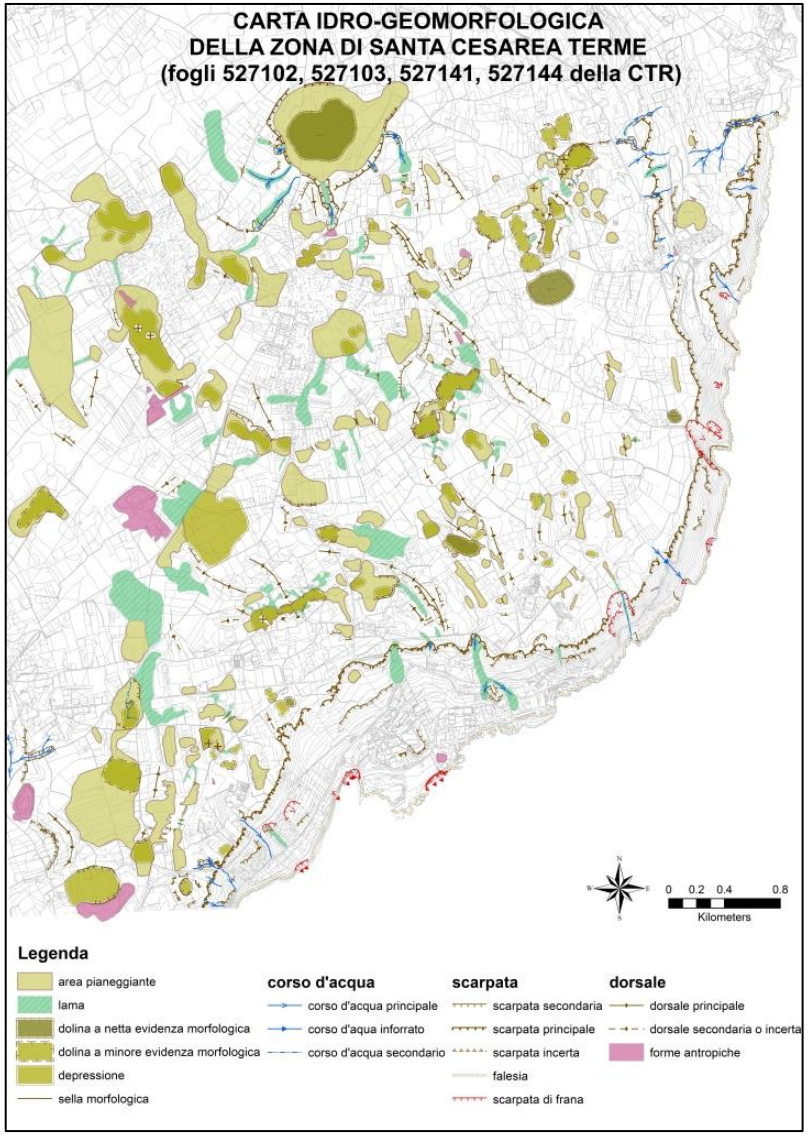
Term mainly used in USA, with mostly engineering meaning

Other names: ***sink, swallet, cenote, sotano, blue hole, tiankeng***

# Examples of geomorphological map in karst areas



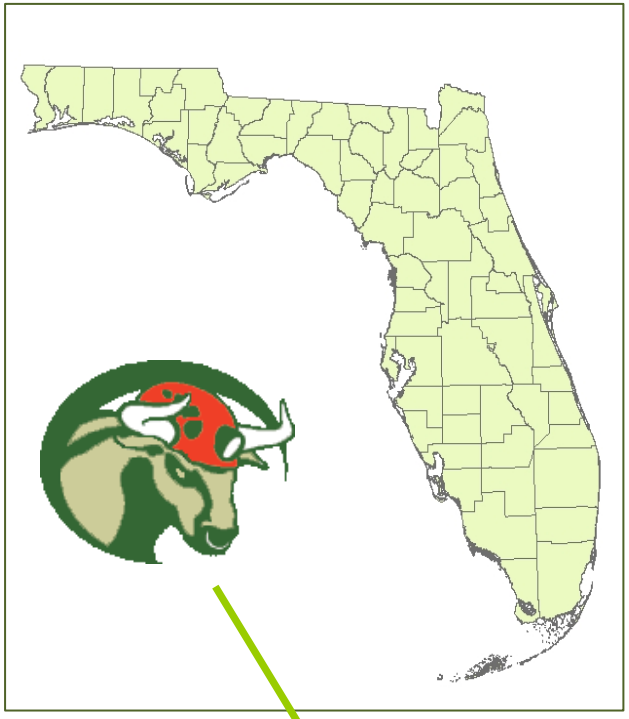



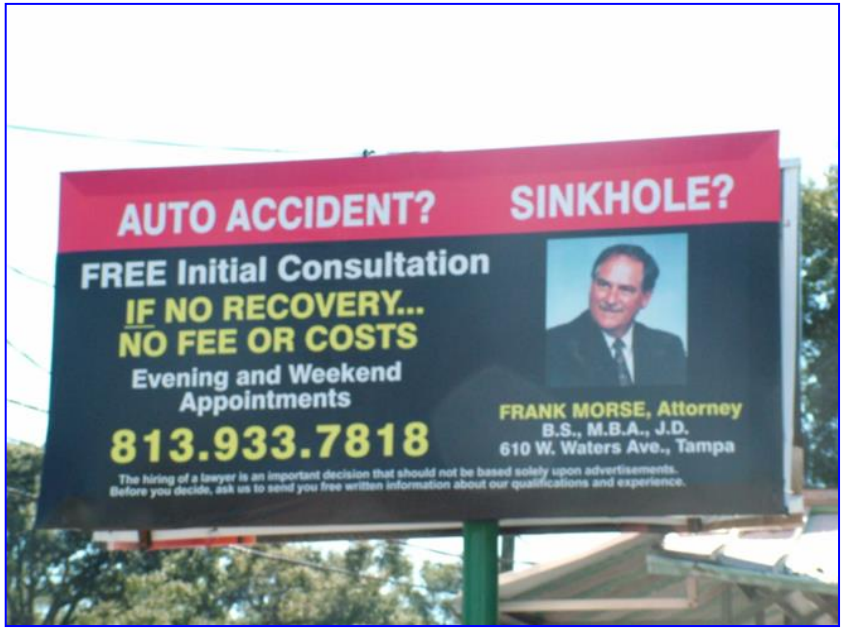

*Pepe & Parise, 2012*


US 285 SOUTH
SUBJECT TO SINKHOLE
1000 FEET AHEAD
62
180
CARLSBAD CAVERNS NATL PARK
KID'S EAT FREE
IHOP
4PM - 10 PM
EVERY DAY

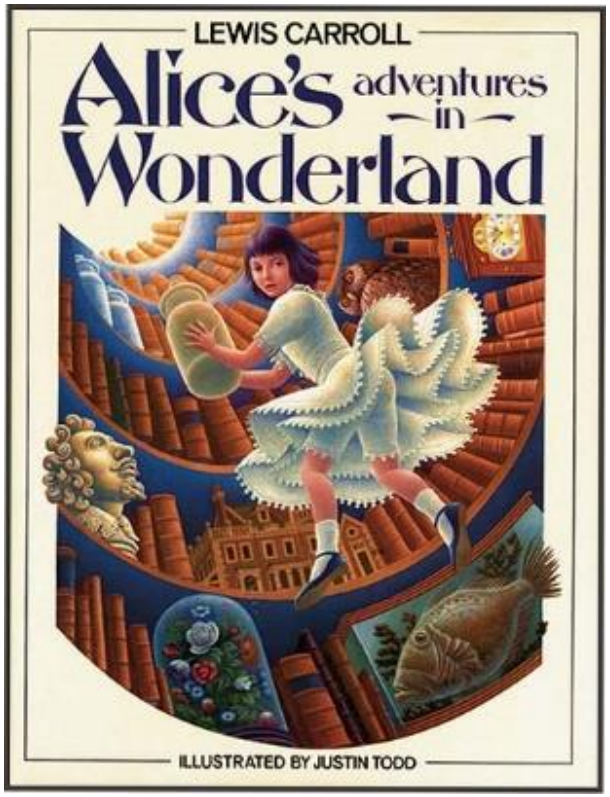
Florida, USA



*Karst Research Group, University of South Florida at Tampa*



# *Reading about .....sinkholes!*



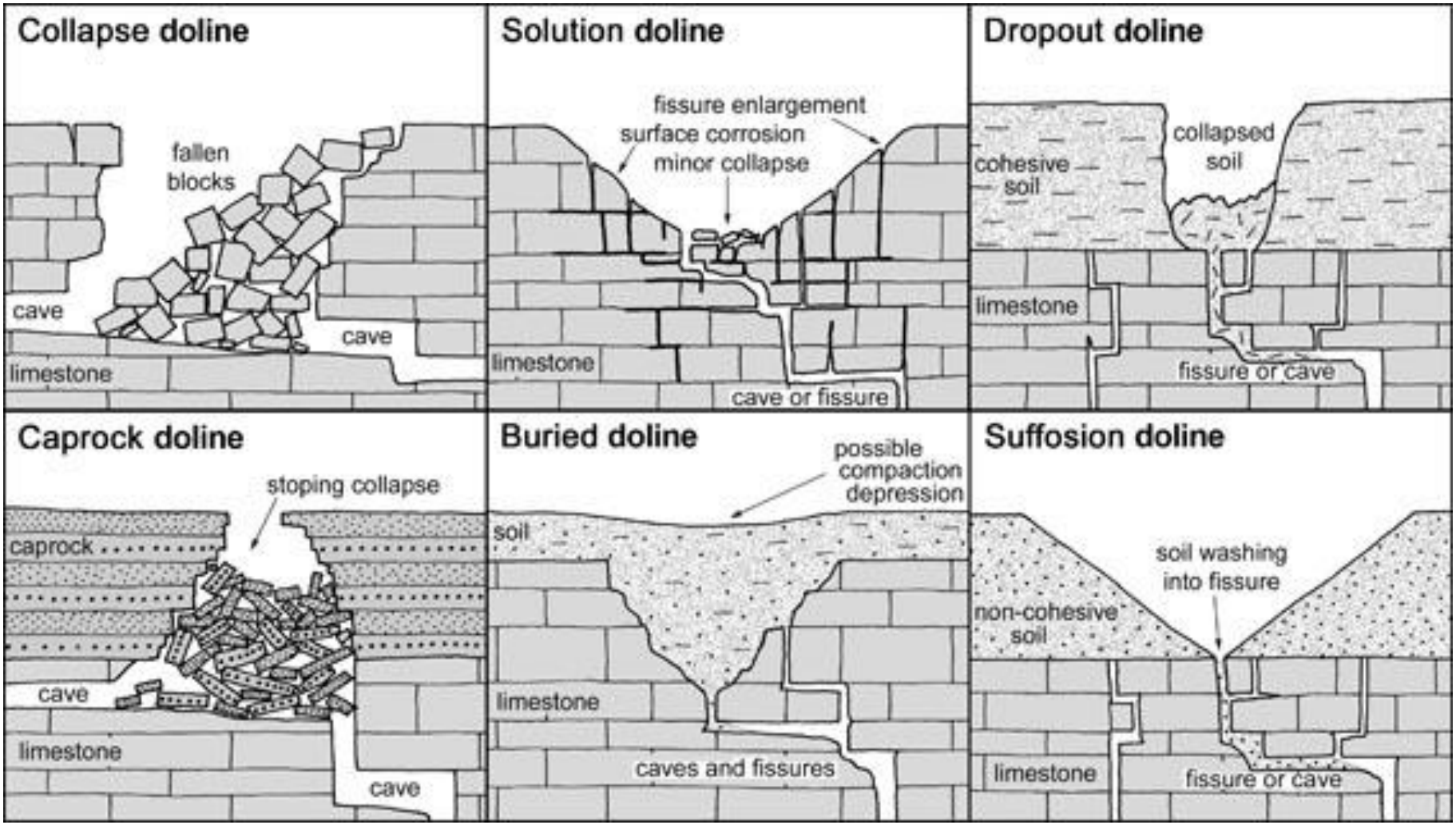

*Lewis Carroll (*pseudonym of Charles Lutwidge Dodgson; 1832-1898).
Write, mathematician, photographer, anglican priest.
Ecletic personality.

He lived in Darlington, not far from Ripon (northern England), area characterized by evaporitic rocks and widespread sinkholes.
Alice's fall into a deep hole, marking the beginning of her fantastic adventures, running after the White Rabbit, has presumably to be linked to one of the many sinkholes in the area.

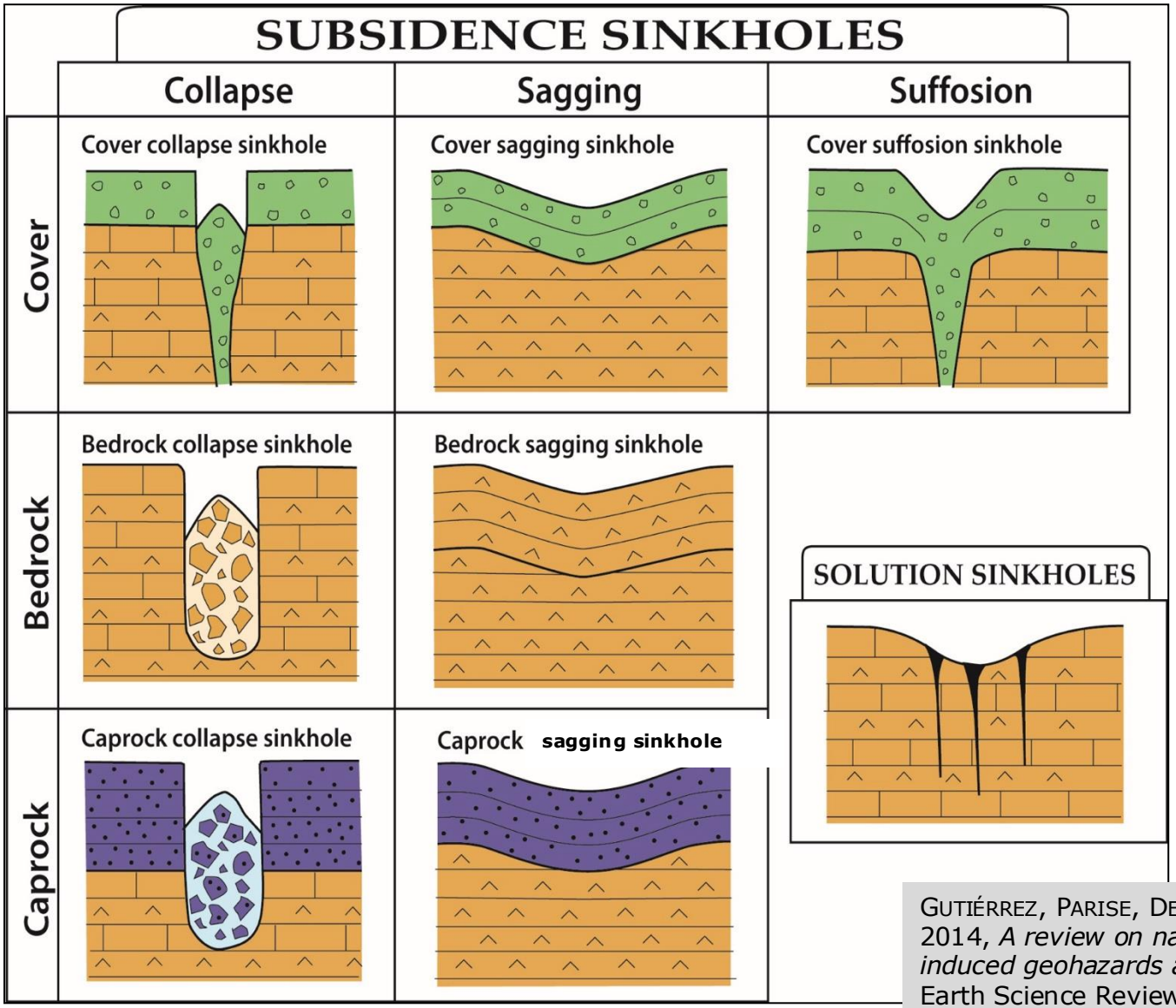
*Sequel*: *Alice's adventures underground*

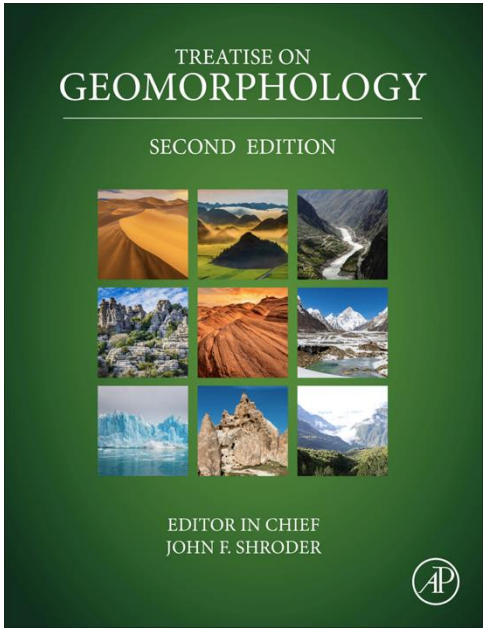
*White Rabbit*

# SINKHOLES




Sinkhole classification (after Waltham et al., 2005)




Re-proposed in PARISE, 2022, *Sinkholes, Subsidence and Related Mass Movements.* Treatise on Geomorphology, vol. 5, p. 200-220.

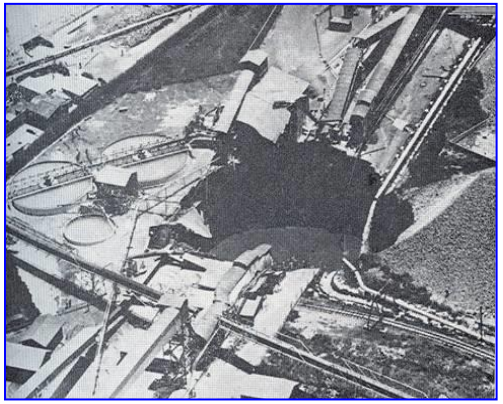
GUTIÉRREZ, PARISE, DE WAELE & JOURDE, 2014, *A review on natural and human-induced geohazards and impacts in karst.* Earth Science Reviews 138, 61-88.

Urali Mountains, Russia

*photo: P. Forti*

Schmalkalden, Germany, 30 October 2010

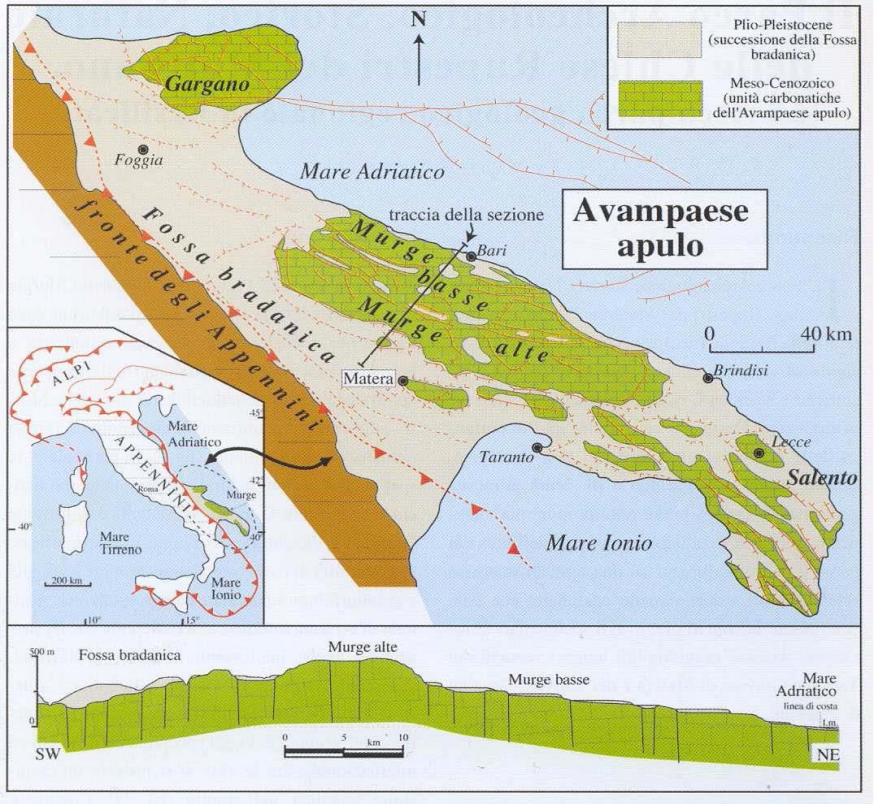
1962, South Africa

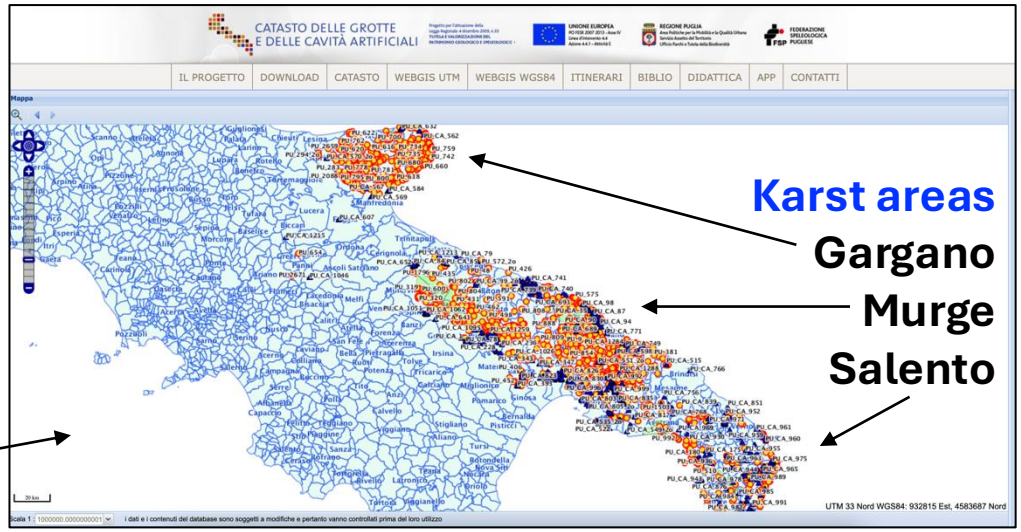


28 February 2013, Florida (240 Faithway Drive in Seffner). Collapse swallowed a person while sleeping in his bedroom. This active sinkhole was previously treated by compaction grouting. Inadequate correction measures may lead to fatal consequences.

# Apulian karst

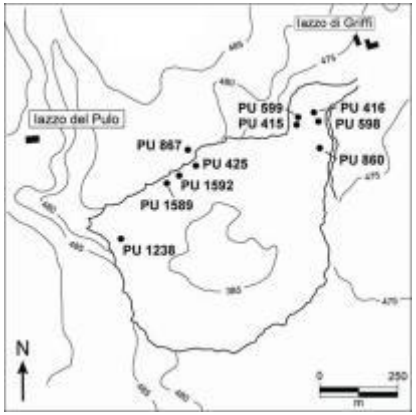

Among the most important sectors in the Mediterranean basin in terms of percentage of outcrop of soluble rocks

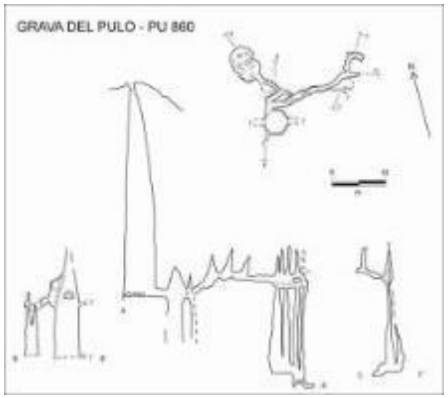



More than 2000 natural caves in the regional register

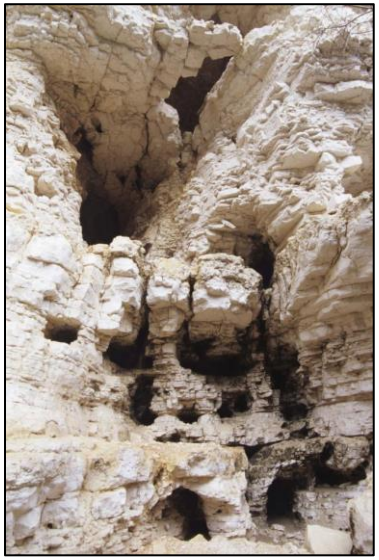
# Pulo di Altamura
(Murge)



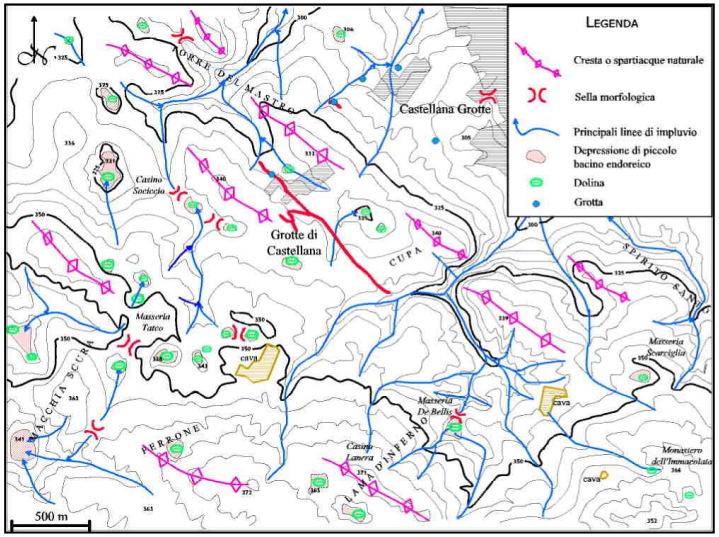

Gurgo di Andria

Pulo di Molfetta



# Castellana-Grotte

Geomorphological map of the Castellana-Grotte area



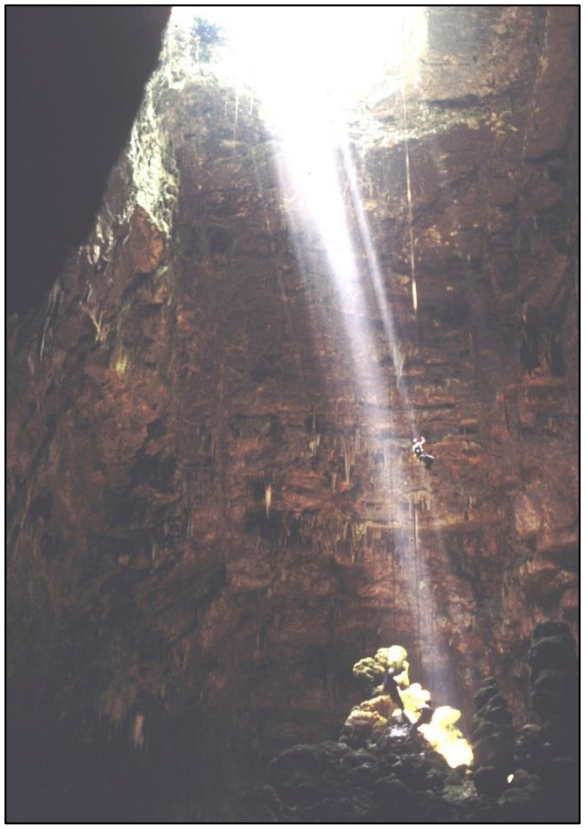
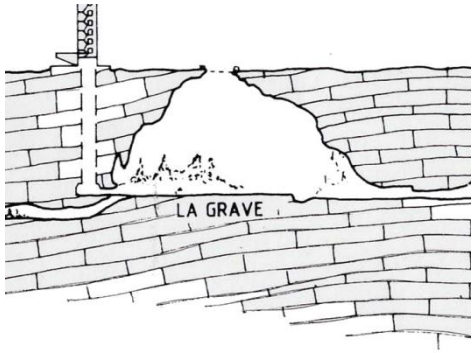
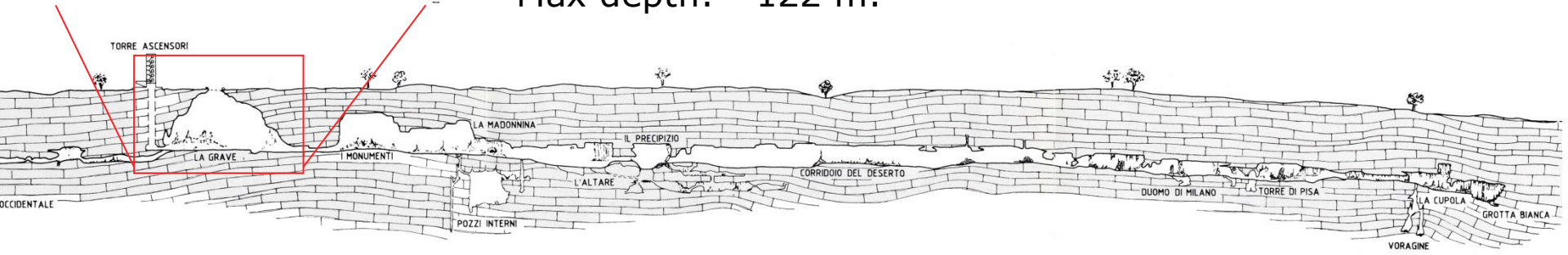



*photo: G. Campanella*



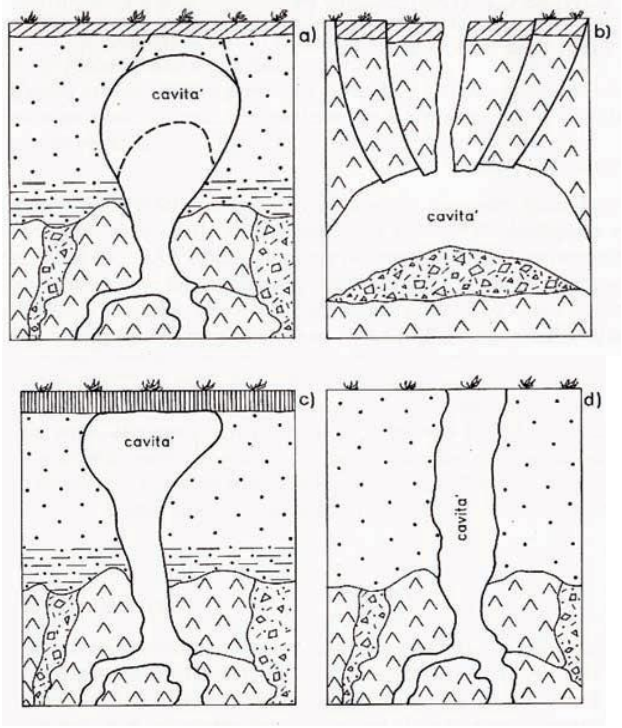

Among the most famous show caves in Italy

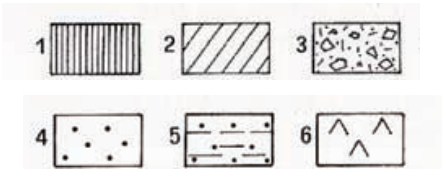
Length: 3250 m.
Max depth: - 122 m.



# *Lesina Lake*

Formation mechanisms of sinkholes (MELIDORO & PANARO, 2000)



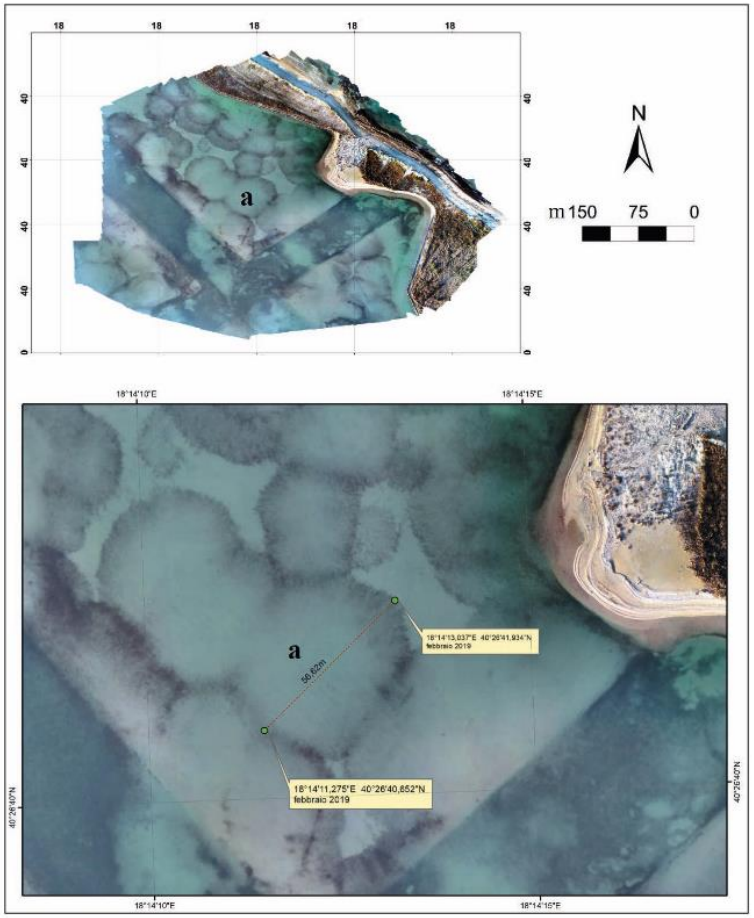




Legend:
1) road;
2) Soil
3) rock blocks in gypsum deposit
4) Sand
5) sand and silt
6) karstified gypsum

Photos: M. Parise

# *Acquatina lagoon*

- Artificial lagoon
- Linear extention: 5628 m
- Area: 424.634 $m^2$
- Use: sanitary to eradicate malaria, fishing and agriculture
- Sinkholes are dominant close to the lagoon internal channels





*hydrology*

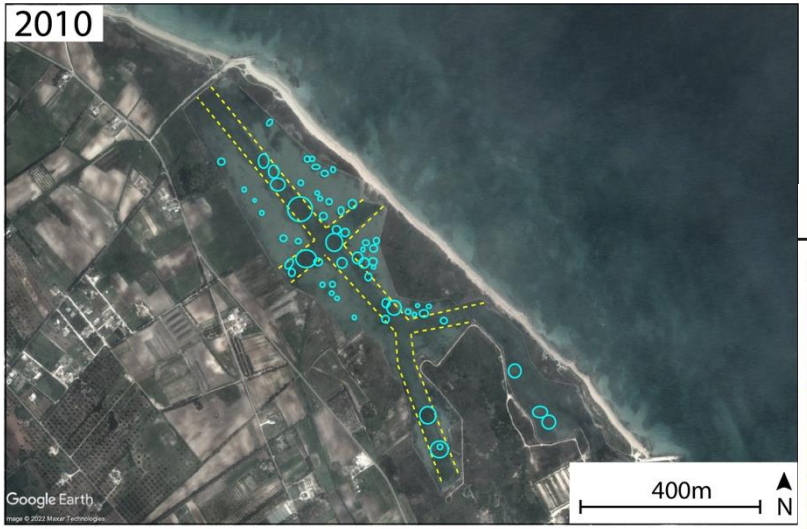
MDPI

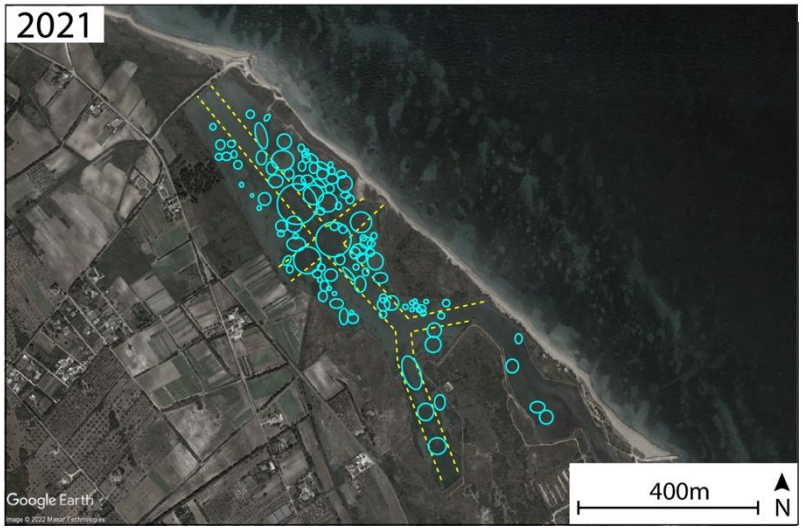
*Article*

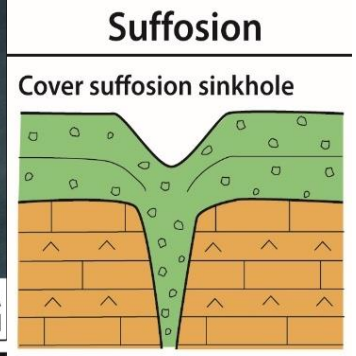
**Hydro-Stratigraphic Conditions and Human Activity Leading to Development of a Sinkhole Cluster in a Mediterranean Water Ecosystem**

Stefano Margiotta [1], Gabriele Marini [1,2], Sergio Fay [3], Francesco M. D'Onghia [4], Isabella S. Liso [5], Mario Parise [5,*] and Maurizio Pinna [1,2]

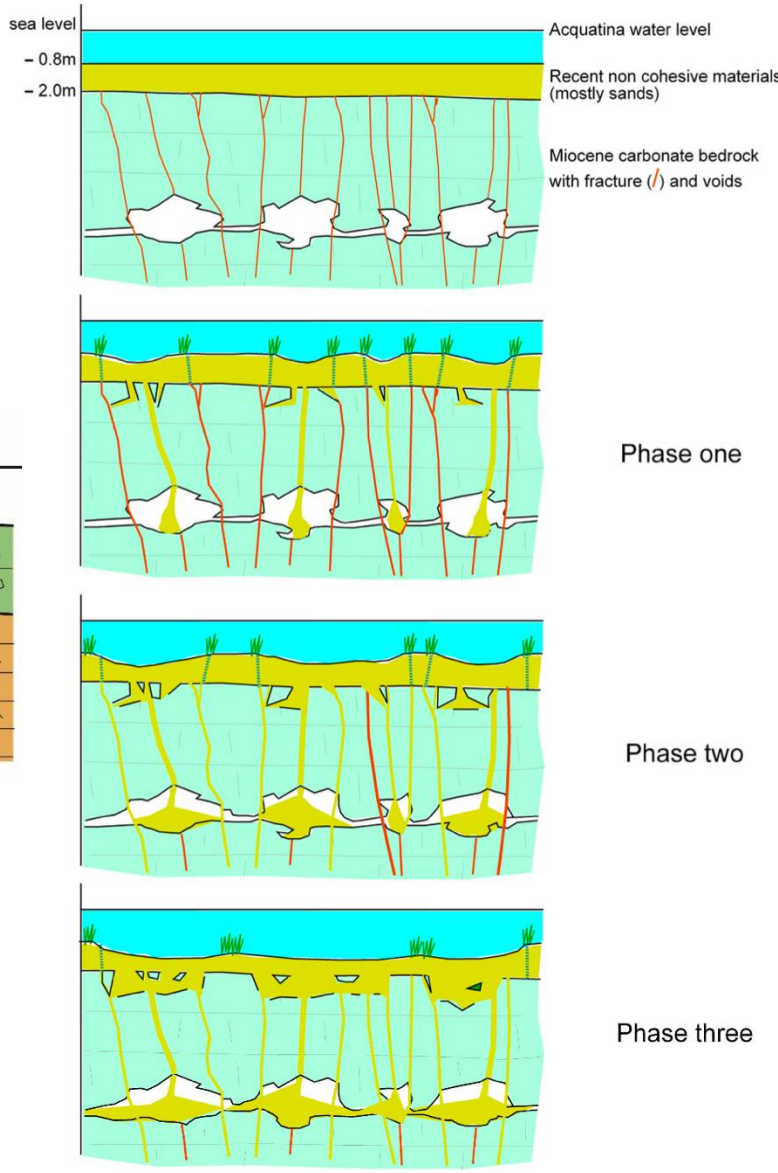
# *Acquatina lagoon*



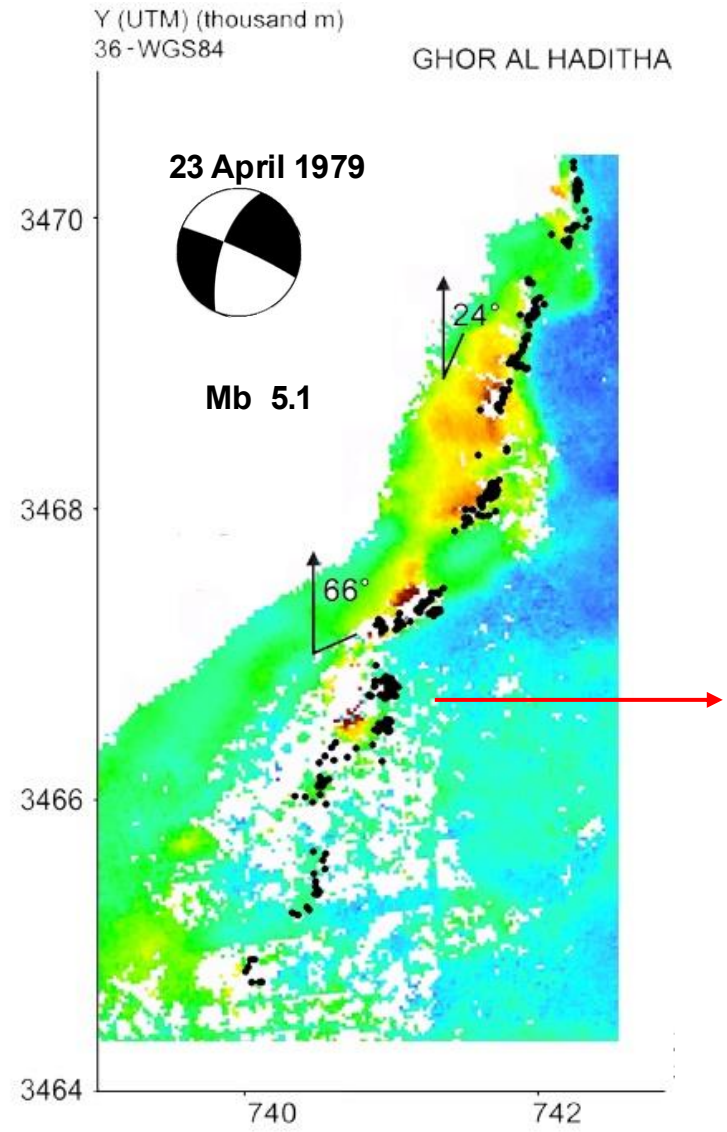




Gutiérrez et al., 2014
Parise, 2022



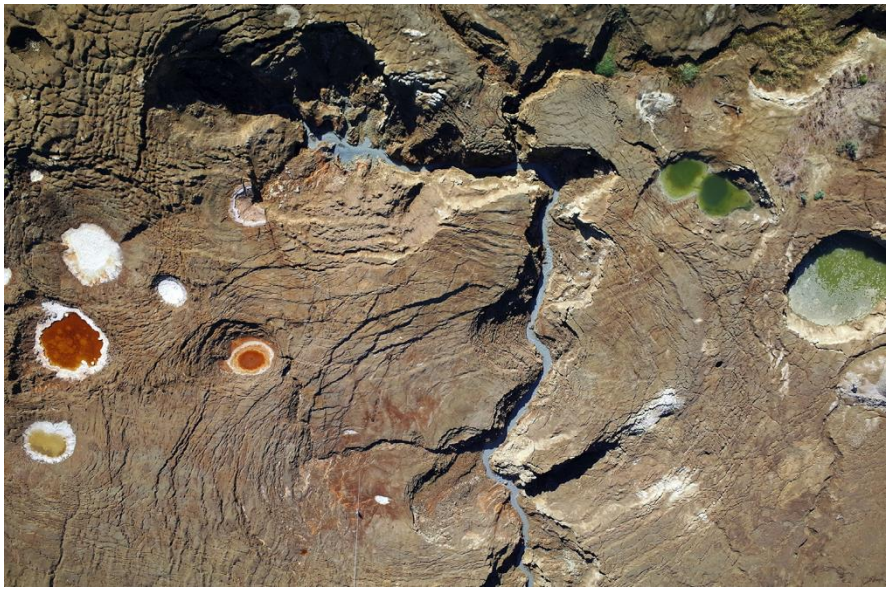

*Margiotta et al., 2021*

# 2009-05-12 / Ghor Al Haditha / Jordan




D. Closson

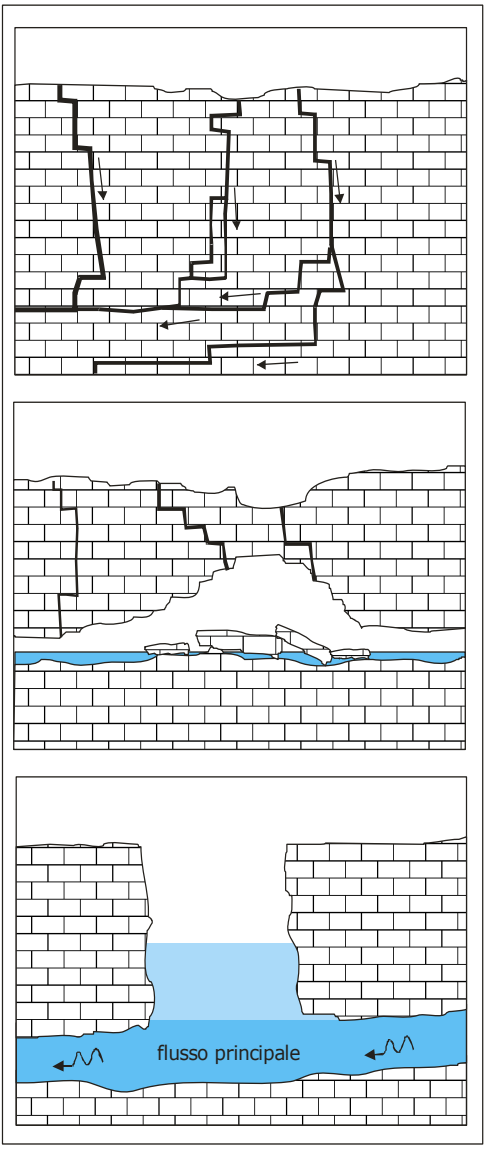
## Eastern Dead Sea, Jordan



photos: D. Al-Halbouni

# CENOTES

## Formation of a *cenote*




Initial phase: Infiltration of meteoric water and mixing with underground waters.

Formation of the first cavities, due to dissolution and later rock failures.

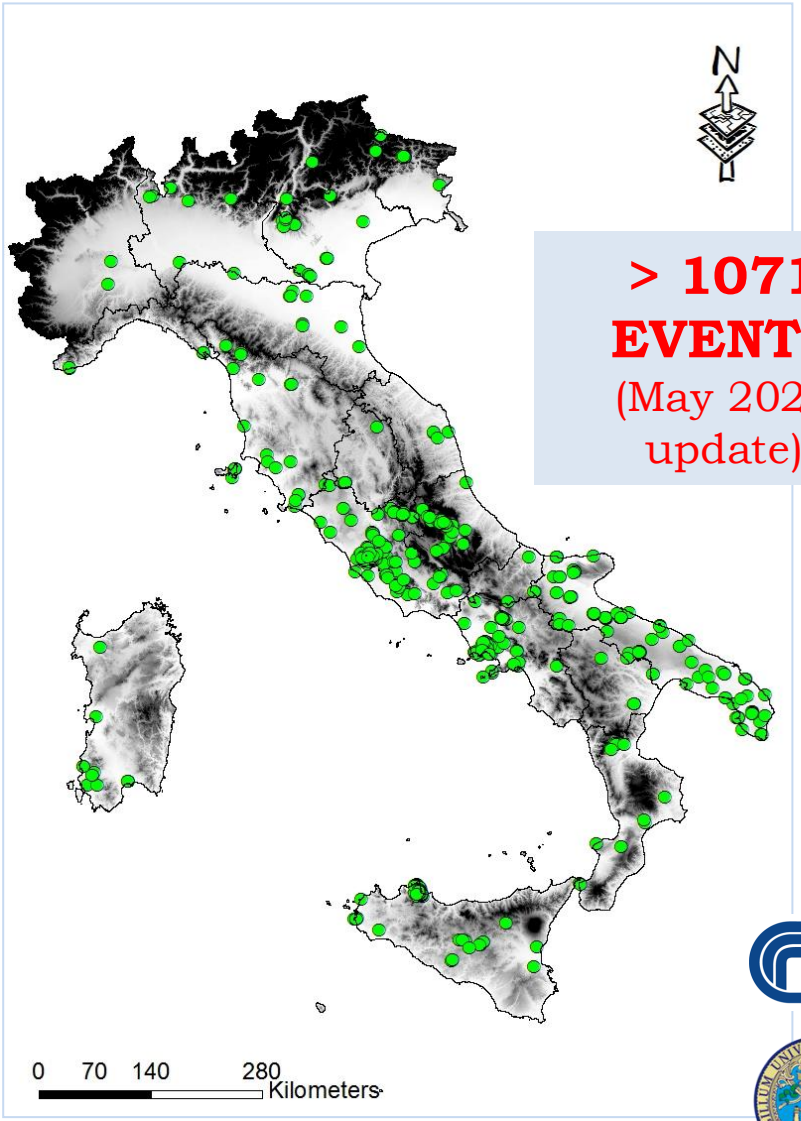
Fall of the diaphragm and removal of breakdown debris by the underground streams. Successive rising of sea level.

Dos Ojos, Messico (photo A. Narduzzi)

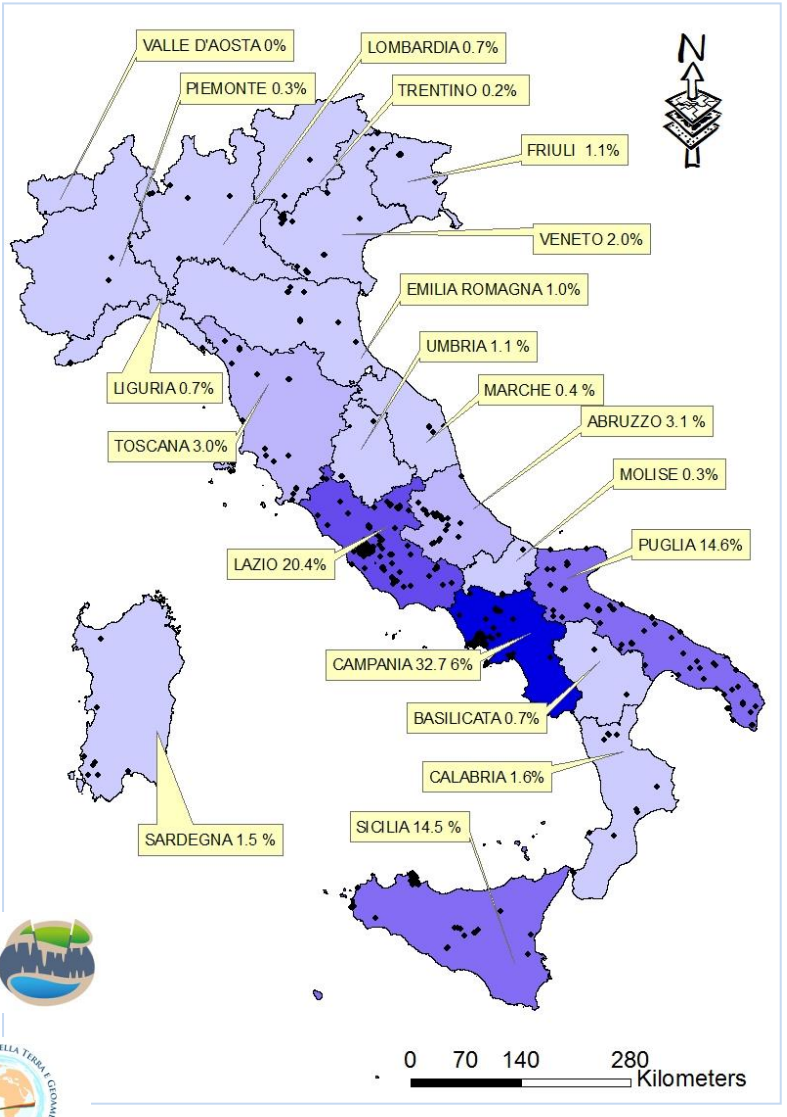
The most extensive flooded system is Sac Actun and Nohoch Nah Chich in Yucatan, Mexico (154 km).
In the great karst plain hundreds of **cenotes** have been formed, reaching the water table, and linking the surface with the flooded galleries.


**Crveno Jezero** (Red lake)
530 m, volume ca. 25–30 millions $m^3$

# Chronological catalogue of Italian sinkholes



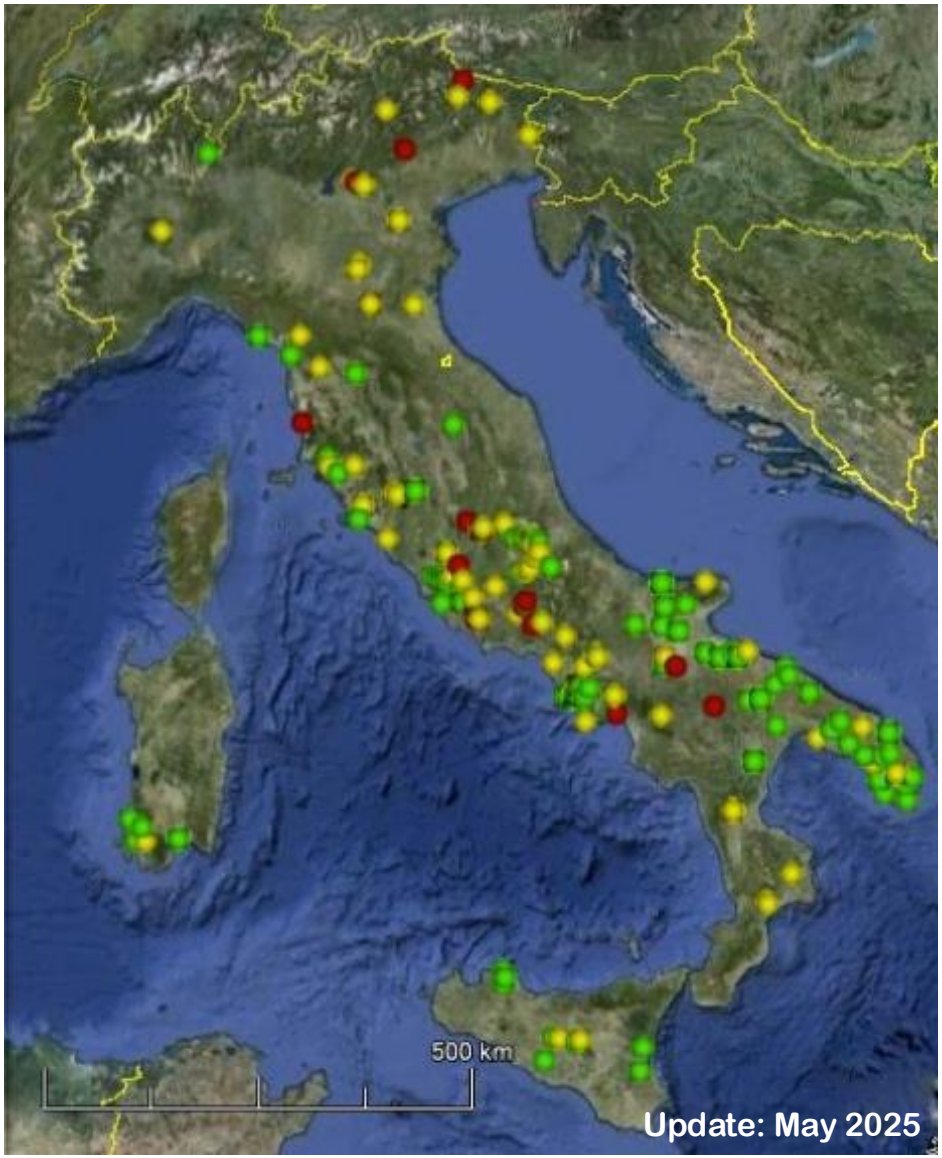

**> 1071 EVENTS**
(May 2025 update)



# Chronological database of sinkholes in Italy

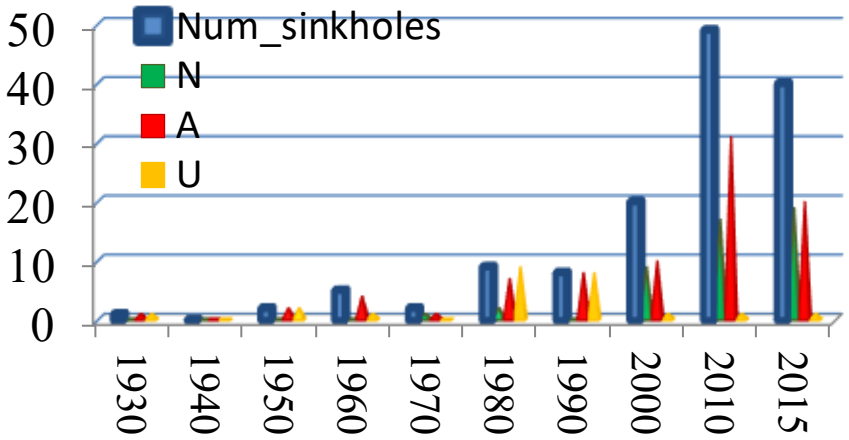
**Goal:**
**assessment of the sinkhole hazard on the Italian territory**

> 1071
documented
events in Italy

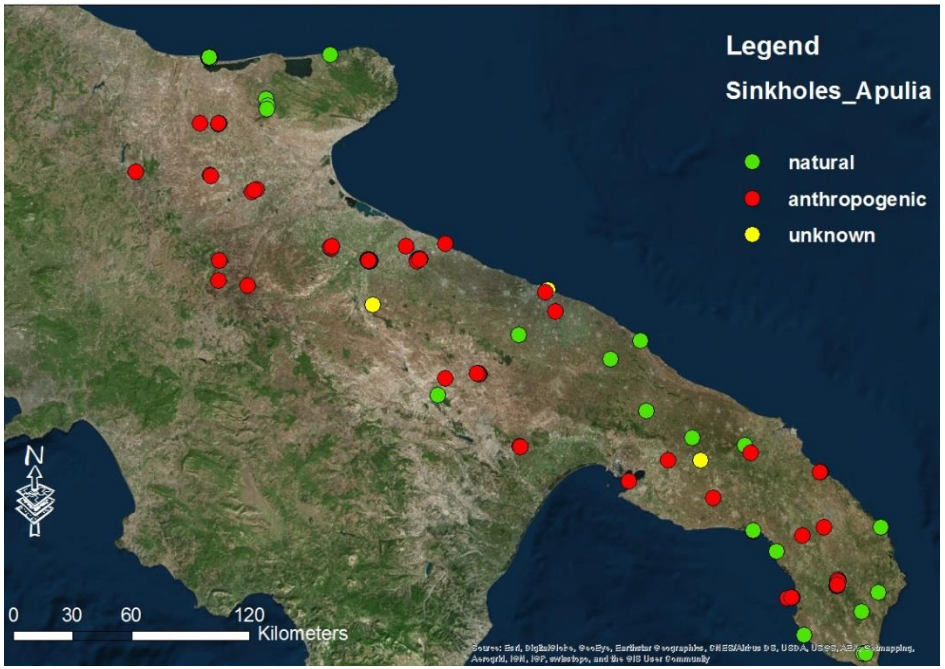


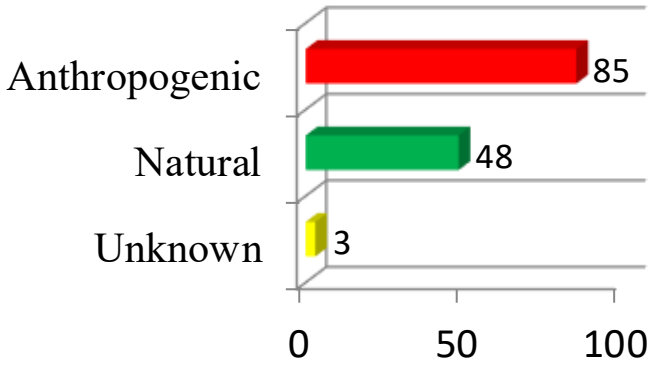

PARISE M. & VENNARI C., 2013, *A chronological catalogue of sinkholes in Italy: the first step toward a real evaluation of the sinkhole hazard.* In: LAND L., DOCTOR D.H. & STEPHENSON B. (Eds.), Proc. 13th Multidisc. Conf. Sinkholes and the Engineering and Environmental Impacts of Karst, Carlsbad (New Mexico, USA), 6-10 May 2013, p. 383-392.

# Chronological catalogue of Italian sinkholes: Apulia




**157 EVENTS** (May 2025 update)




geosciences
MDPI
Article

**A Chronological Database about Natural and Anthropogenic Sinkholes in Italy**

Carmela Vennari [1,*] and Mario Parise [2]

# Sinkhole at Masseria Forte Morello

Sinkhole in a rural area.
5 phases identified in the sinkhole development, with progressive movement of the depocenter toward SSW.

The sinkhole seems to be developed along a zone of fragile tectonics in correspondance of a direct fault.

*photo: M. Sammarco*

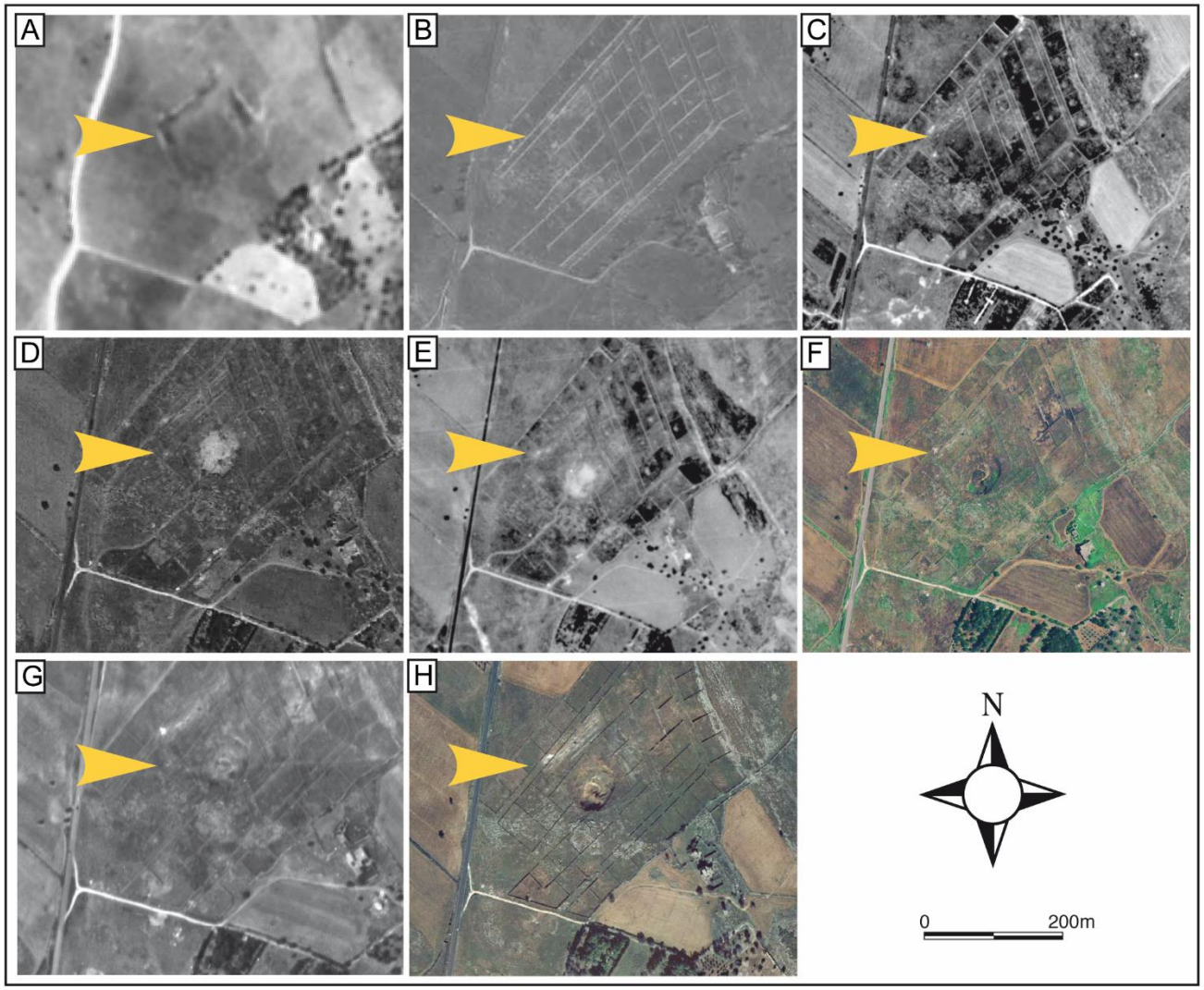



Fig. 6 - Festa et al.

A: 1955
B: 1972
C: 1987
D: 1994
E: 1996
F: 2000
G: 2003
H: 2006

FESTA V., FIORE A., PARISE M. & SINISCALCHI A., 2012, *Sinkhole evolution in the Apulian karst of southern Italy: a case study, with some considerations on sinkhole hazards.*
Journal of Cave and Karst Studies, vol. 74 (2), p. 137-147.

# Sinkhole at Masseria Forte Morello

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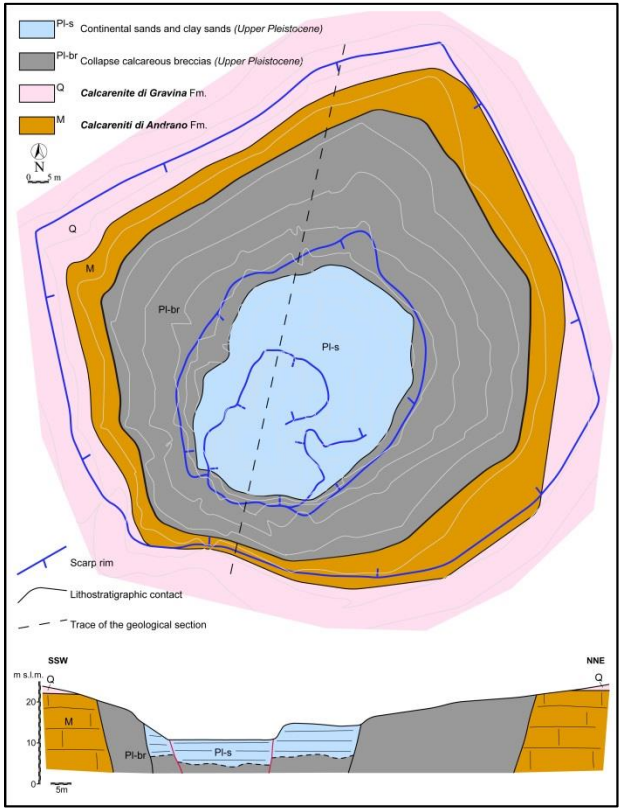
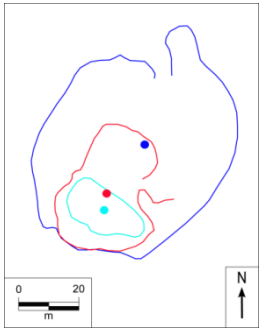
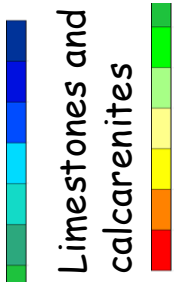
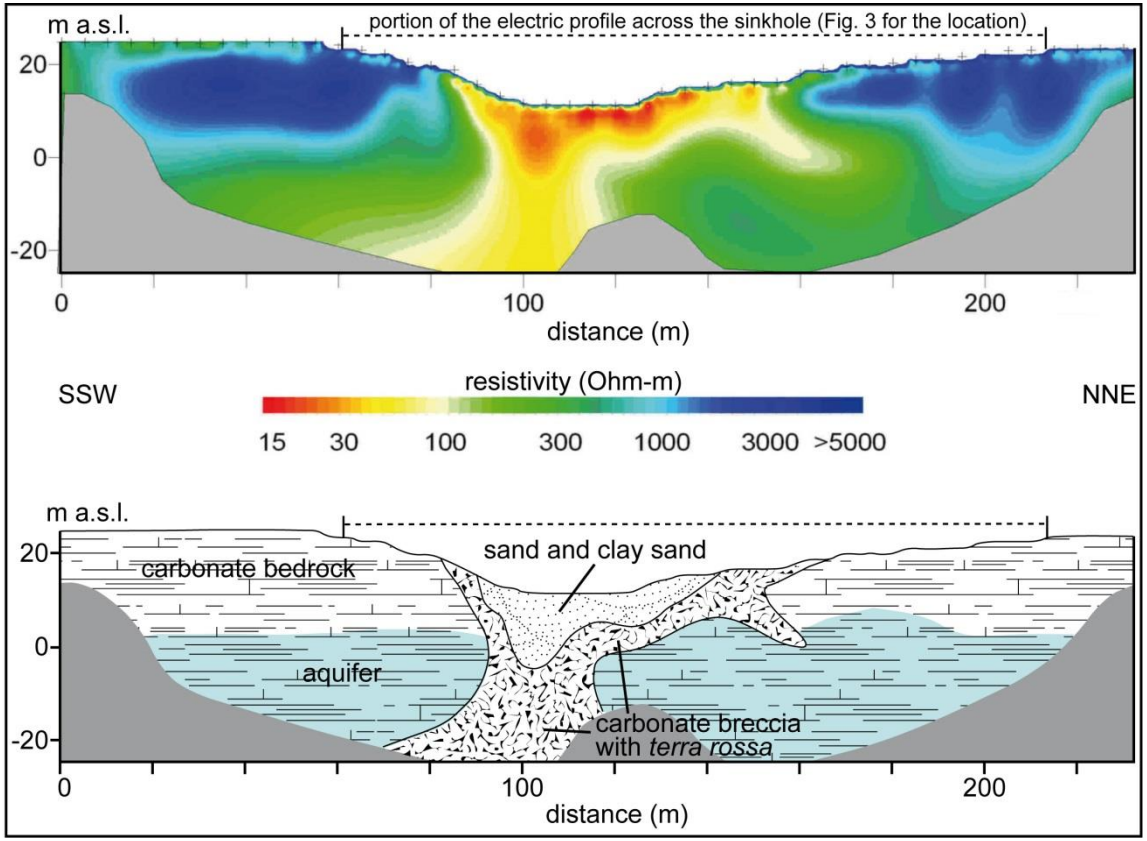
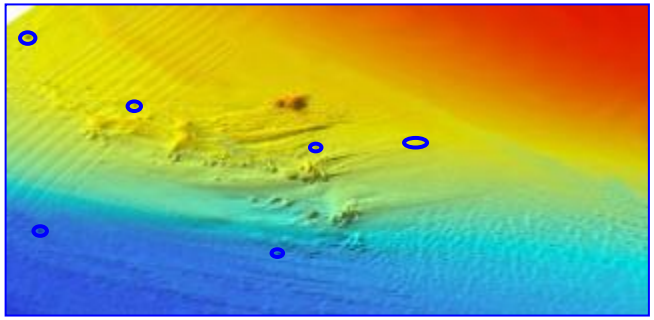


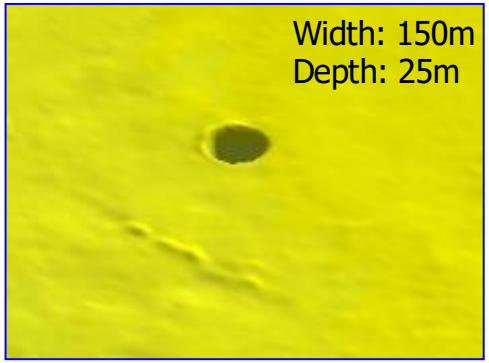



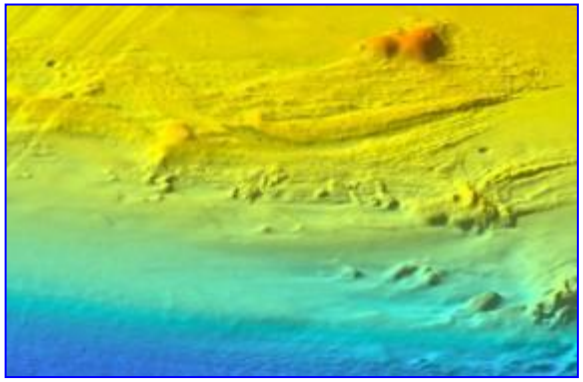



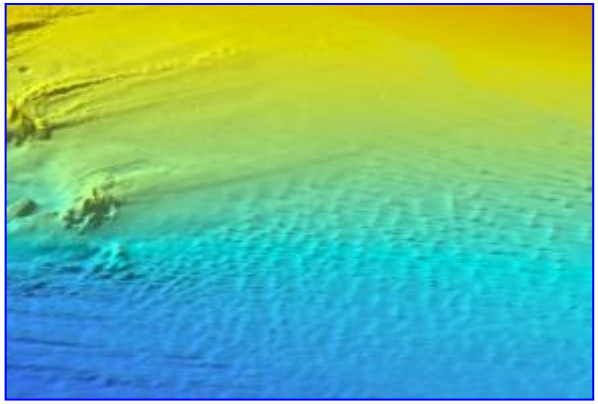



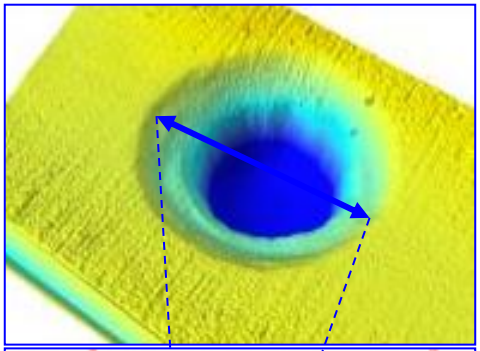
# A glimpse underwater...

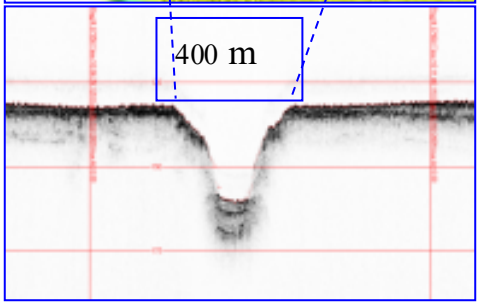



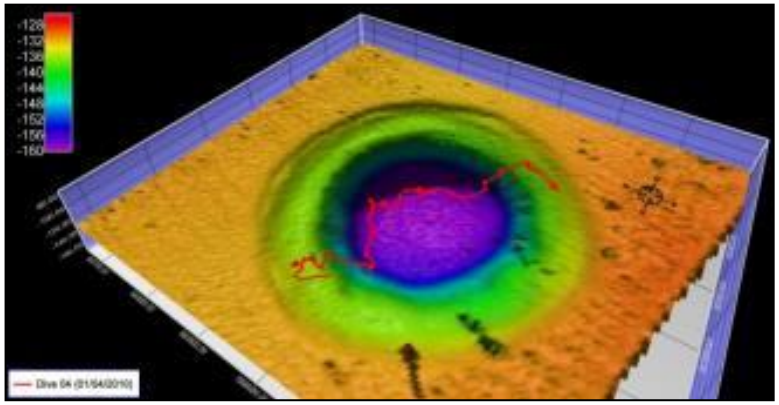








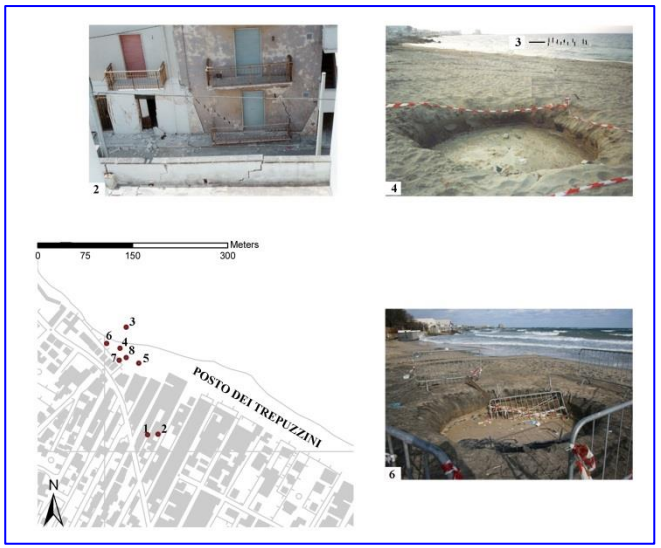
TAVIANI M., ANGELETTI L., CAMPIANI E., CEREGATO A., FOGLINI F., MASELLI V., MORSILLI M., PARISE M. & TRINCARDI F., 2012, *Drowned karst landscapes offshore the Apulian Margin (Southern Adriatic Sea, Italy).* J. Cave and Karst Studies, 74 (2), 197-212.


Apulia:
865 km
of coastline
length

Casalabate

Torre Castiglione

# Casalabate




Nat Hazards (2012) 62:657–676
DOI 10.1007/s11069-012-0100-1

ORIGINAL PAPER

**Mapping the susceptibility to sinkholes in coastal areas, based on stratigraphy, geomorphology and geophysics**

S. Margiotta · S. Negri · M. Parise · R. Valloni

Since the ’90s, repeated sinkhole events, with damage to many buildings

# Torre Castiglione

# Torre Castiglione

Available online at www.sciencedirect.com
ScienceDirect
Engineering Geology 99 (2008) 198–209
ENGINEERING GEOLOGY
www.elsevier.com/locate/enggeo
ELSEVIER

Development and morphometry of sinkholes in coastal plains of Apulia, southern Italy. Preliminary sinkhole susceptibility assessment

E. Bruno [a], D. Calcaterra [a,*], M. Parise [b]

Environ Earth Sci
DOI 10.1007/s12665-013-2297-z
ORIGINAL ARTICLE

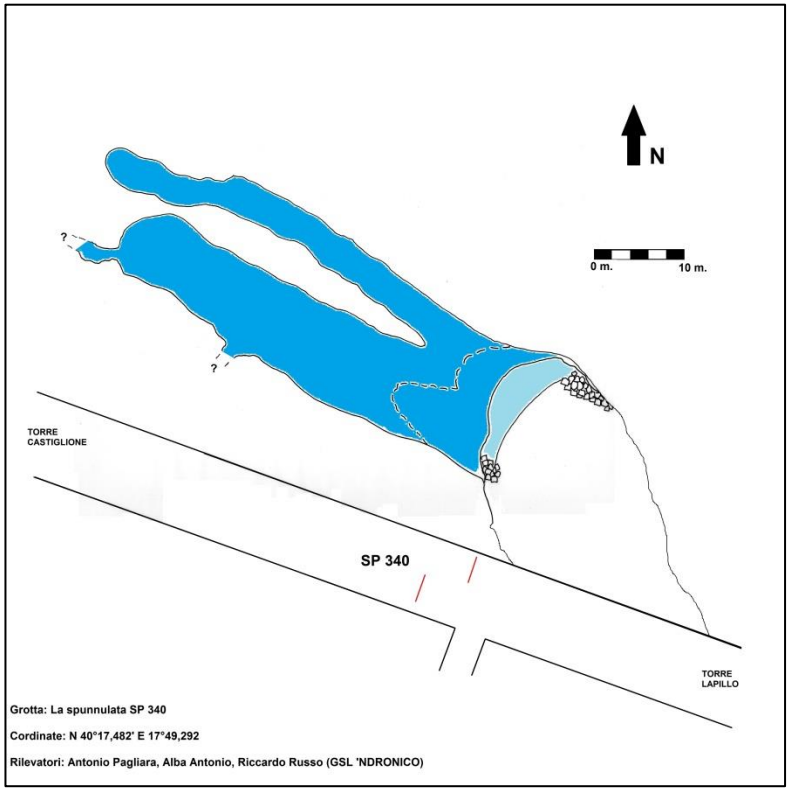
**Morphometric analysis of sinkholes in a karst coastal area of southern Apulia (Italy)**

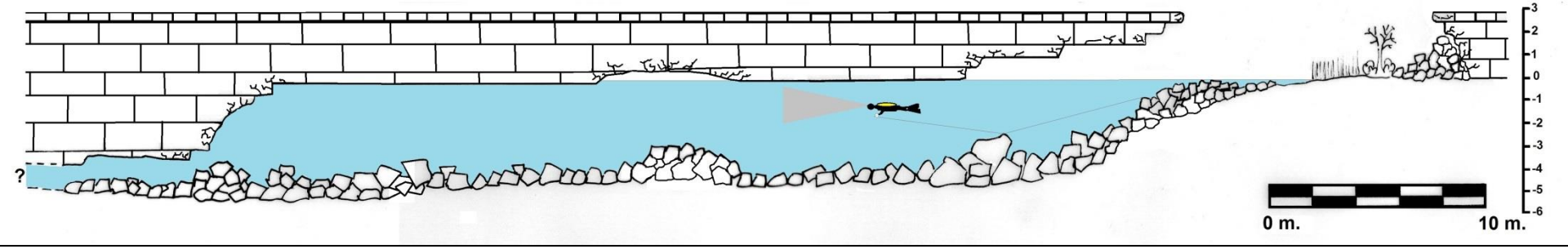
A. Basso · E. Bruno · M. Parise · M. Pepe

*Bruno et al., 2008*
*Basso et al., 2013*

# Torre Castiglione

Flooded galleries, 4-5 m-high, 5-9 m-wide, at least 36-50 m-long



## SPUNNULATA DELLA PAJARA Pu/LE 1809

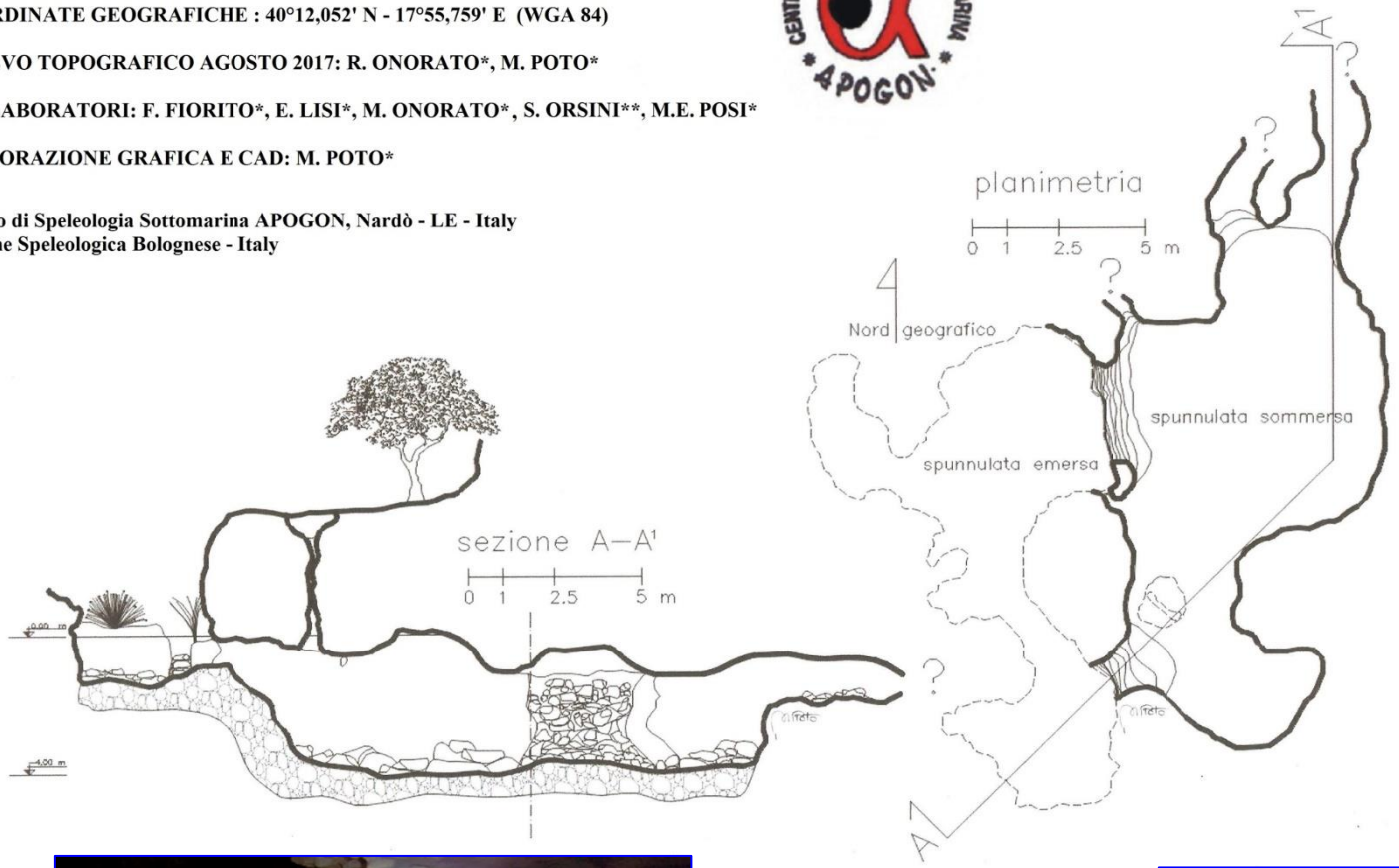
**COMUNE DI NARDO' - LE - ITALY - LOC. PALUDE DEL CAPITANO**
**COORDINATE GEOGRAFICHE : 40°12,052' N - 17°55,759' E (WGA 84)**

**RILIEVO TOPOGRAFICO AGOSTO 2017: R. ONORATO*, M. POTO***

**COLLABORATORI: F. FIORITO*, E. LISI*, M. ONORATO* , S. ORSINI**, M.E. POSI***

**ELABORAZIONE GRAFICA E CAD: M. POTO***


*** Centro di Speleologia Sottomarina APOGON, Nardò - LE - Italy**
****Unione Speleologica Bolognese - Italy**


*Parise et al., 2017*

Grotta Sfondata
PU 922

Guatemala City

# Artificial Cavities

ARTIFICIAL CAVITIES *are subterranean works <u>of historical and anthropological interest</u>, realized or re-adapted by man, diversified for epoch and technique of realization and purpose of use*.

photo: M. Traverso

photo: F. Milla

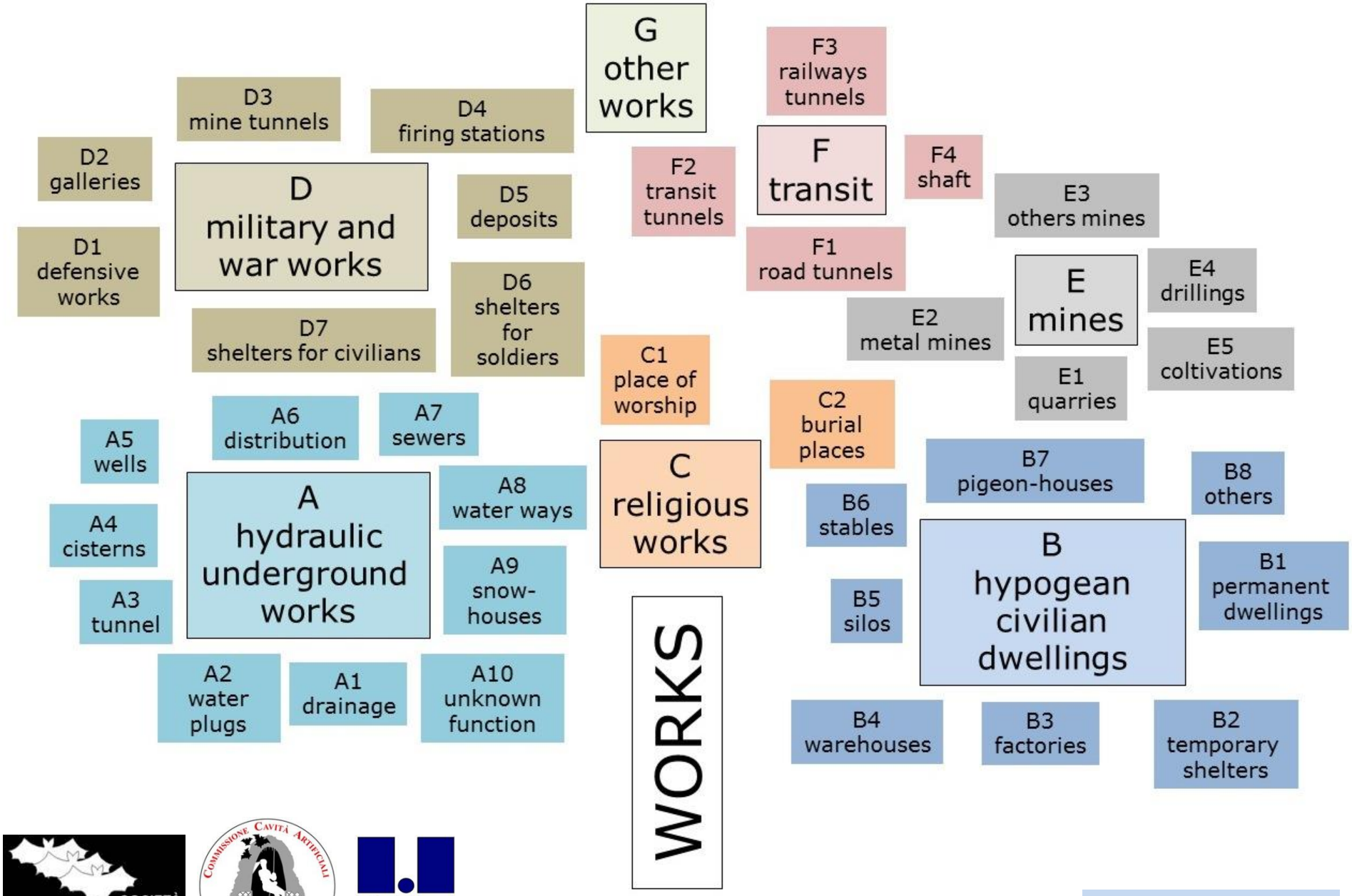
https://artificialcavities.com

Members Projects Links Documents Photos

# Artificial Cavities Commission

## Artificial Cavities Commission – Department of Scientific Research – UIS

https://www.operaipogea.it/en/home-en/

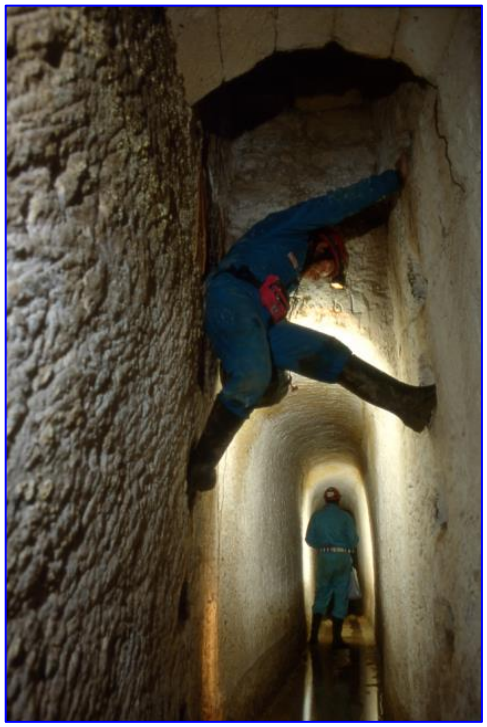


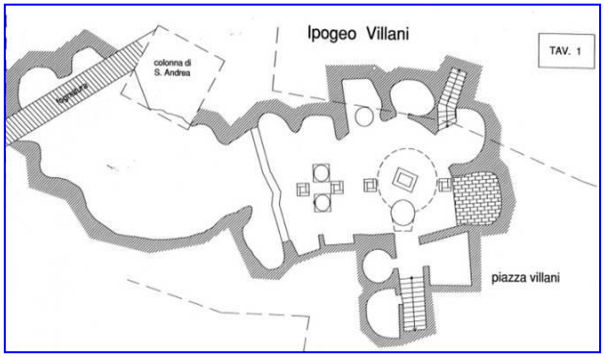

SOCIETÀ SPELEOLOGICA ITALIANA

COMMISSIONE CAVITÀ ARTIFICIALI
Storia Cultura Civiltà Ambiente

*Parise et al., 2013;*
*Galeazzi et al., 2025*

# Hypogean civilian dwellings




Ipogeo Villani
TAV. 1
colonna di
S. Andrea
piazza villani

# Underground quarries in Apulia

Underground quarries are the type of artificial caves that has caused the highest number of sinkholes in the region.

They are present over the whole regional territory, from Gargano to Murge, and Salento.

# Underground quarries in Apulia

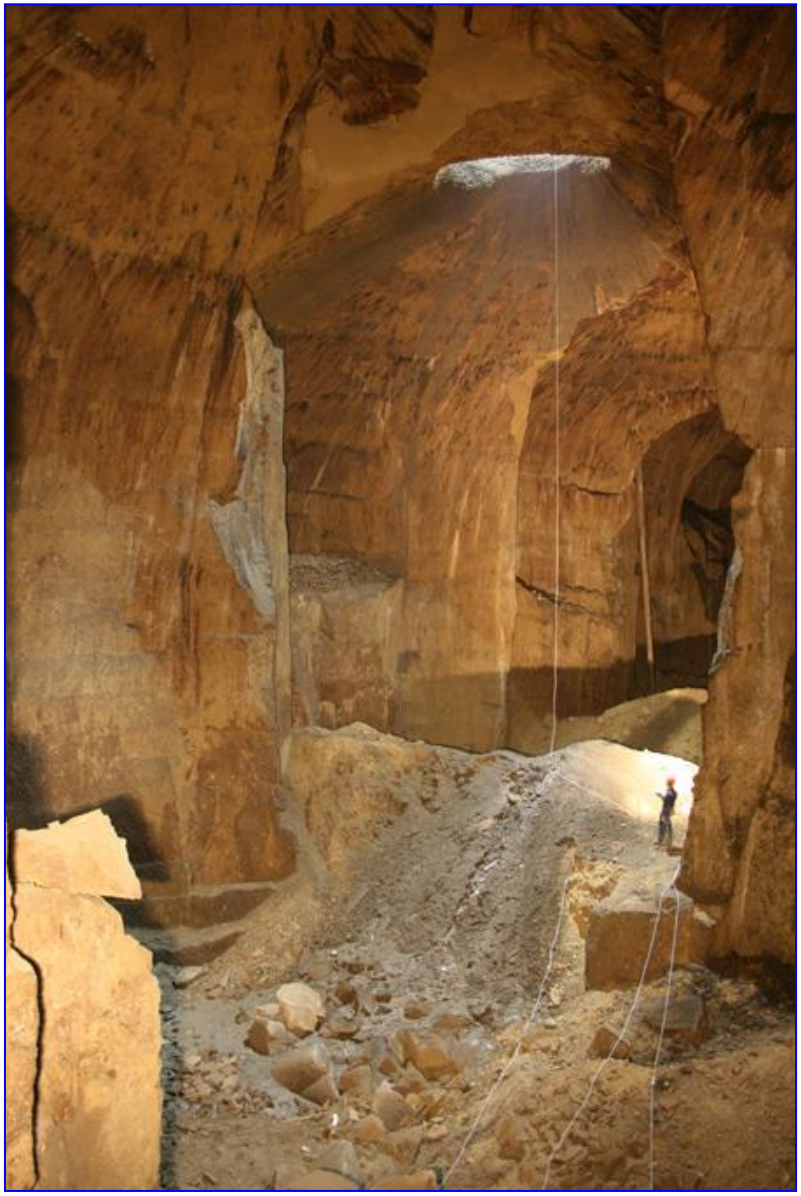


photo: B. Bocchino

Main reasons for **underground quarrying**:

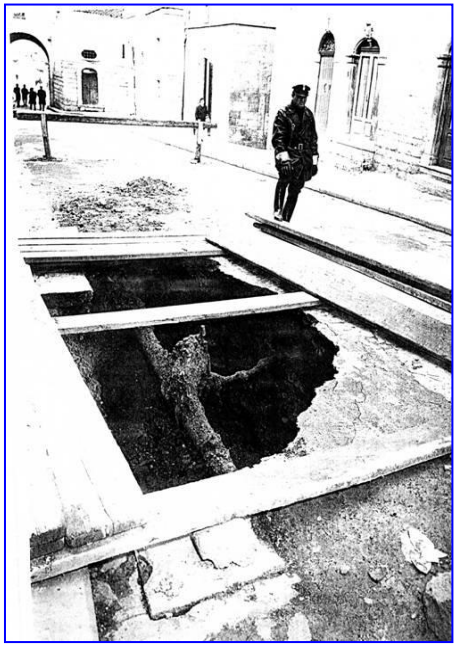
- presence of the rocks with the best characteristics at a certain depth, not exposed at the surface;
- the need to preserve surface lands to be used for agriculture.

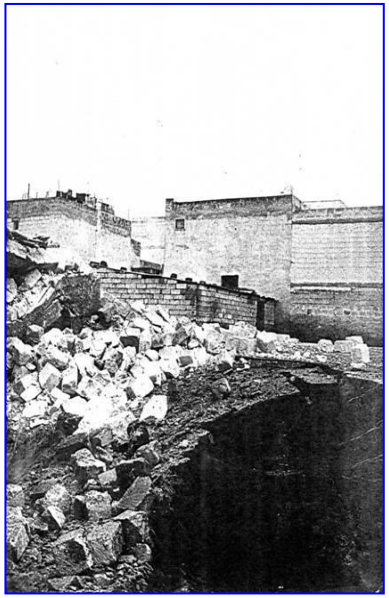
photo: S. Del Prete

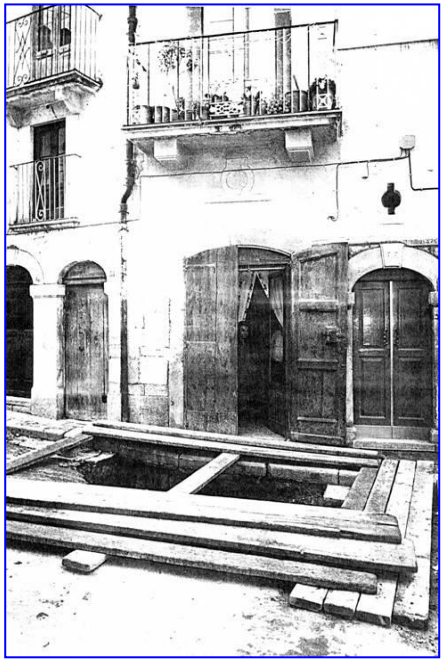
Chronology of documented sinkhole events related to underground quarries

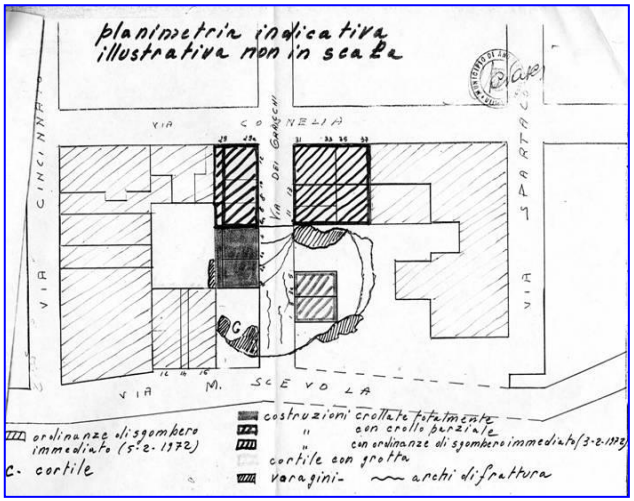
| LOCALITY | DATE |
|---|---|
| CANOSA DI PUGLIA | 1925 |
| ALTAMURA | 1947 |
| CANOSA DI PUGLIA | March 8, 1955 |
| CUTROFIANO | July 1956 |
| CANOSA DI PUGLIA | April 8,1957 |
| CUTROFIANO | May-June 1957 |
| ANDRIA | November 27, 1959 |
| ANDRIA | February 3, 1972 |
| ANDRIA | October 13-14, 1972 |
| ANDRIA | December 11, 1972 |
| ANDRIA | July 21, 1973 |
| ANDRIA | May 5, 1974 |
| ANDRIA | February 20, 1980 |
| CUTROFIANO | before April 1985 |
| CANOSA DI PUGLIA | 1986 |
| CANOSA DI PUGLIA | May 4, 1990 |
| CUTROFIANO | February 1996 |
| CANOSA DI PUGLIA | September 5, 1999 |
| ALTAMURA | March, 2006 |
| GALLIPOLI | March 29, 2007 |
| ALTAMURA | May 7, 2007 |
| CUTROFIANO | July 15, 2008 |
| ALTAMURA | December 3, 2008 |
| GINOSA IN PUGLIA | February, 2009 |
| CUTROFIANO | March 2010 |
| BARLETTA | May 3, 2010 |
| CUTROFIANO | May 2010 |
| CUTROFIANO | October, 2010 |
| GALLIPOLI | November, 2010 |
| ALTAMURA | December 1, 2013 |
| GALLIPOLI | December 1, 2013 |
| ALTAMURA | March 7, 2015 |

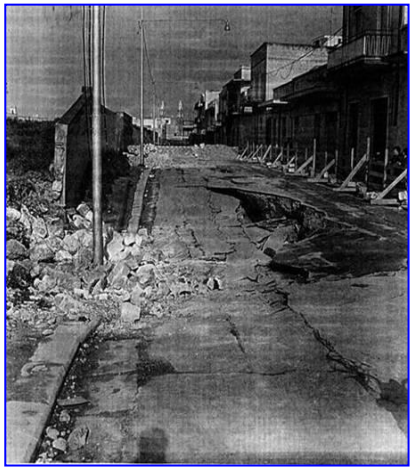
# Andria



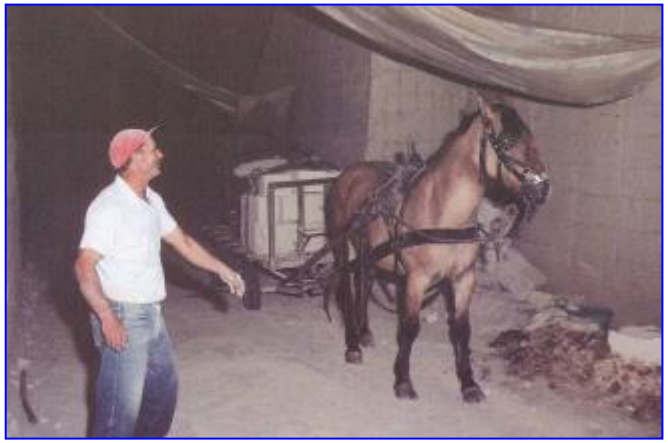





planimetria indicativa
illustrativa non in scala
VIA CINCINNATO
VIA CORNELIA
VIA SPARTACO
VIA M. SCEVOLA
C. cortile
ordinanze di sgombero immediato (5-2-1972)
costruzioni crollate totalmente
" con crollo parziale
" con ordinanze di sgombero immediato (3-2-1972)
cortile con grotta
voragini
archi di frattura



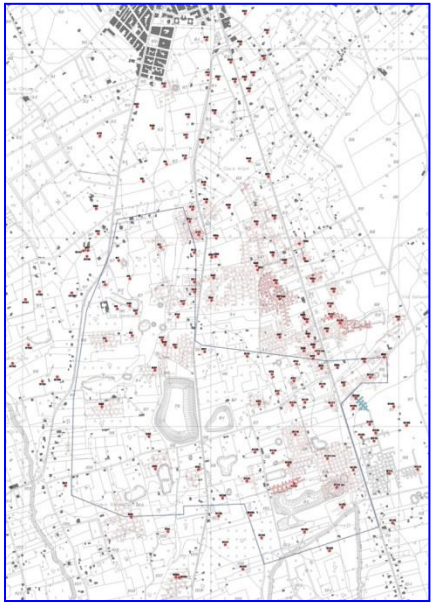
# Cutrofiano



*Toni, 1985*

# Cutrofiano

July 2008

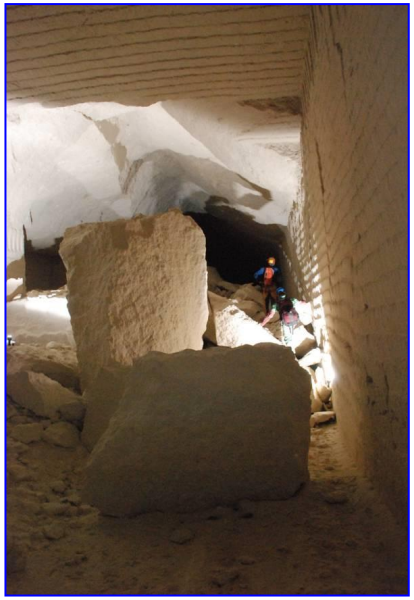


October 2010

March 2010

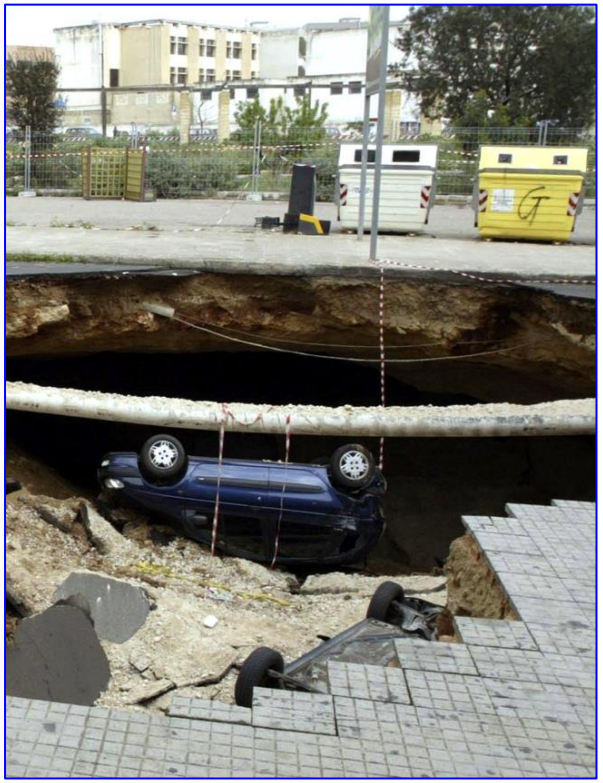
*photo: G. Quarta*

# Cutrofiano



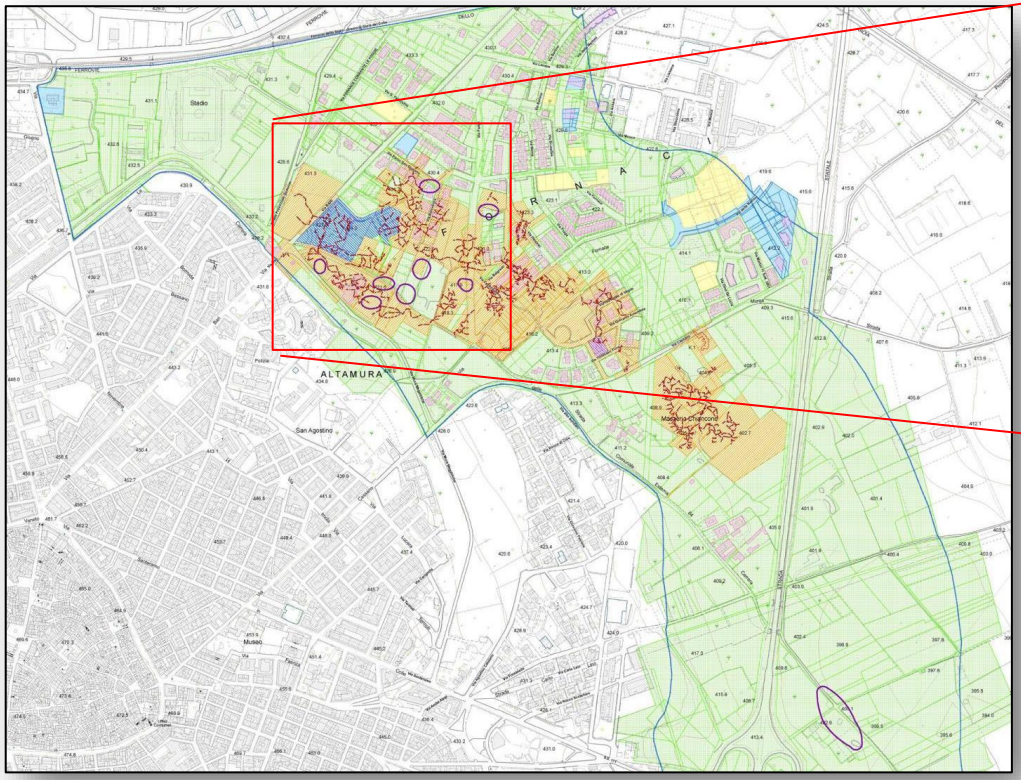
# Gallipoli

29 March 2007



PARISE M., 2012, *A present risk from past activities: sinkhole occurrence above underground quarries.*
Carbonates and Evaporites, vol. 27 (2), p. 109-118.

# Altamura



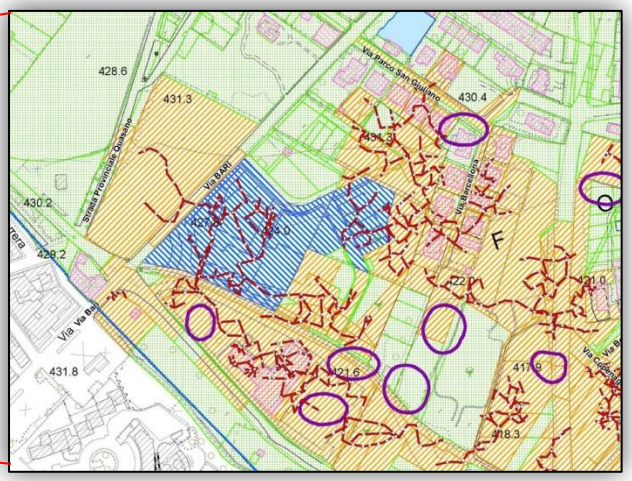
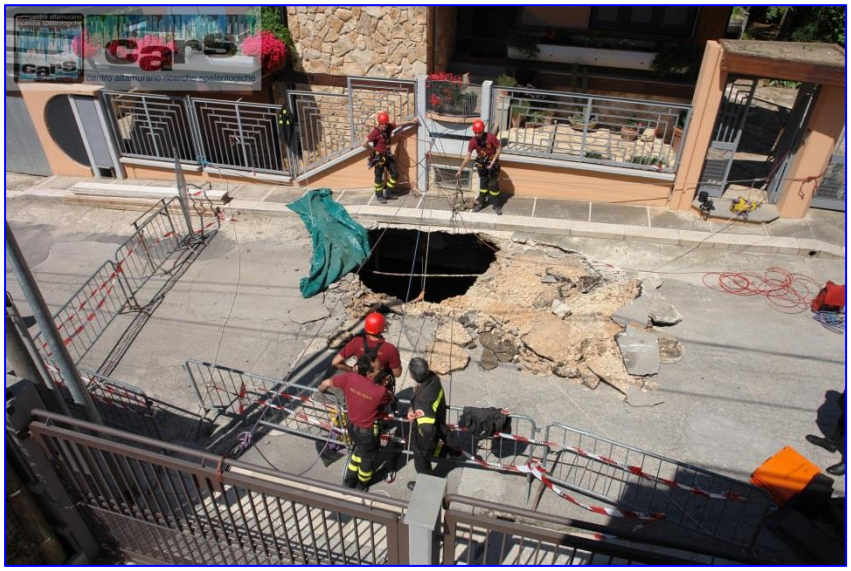





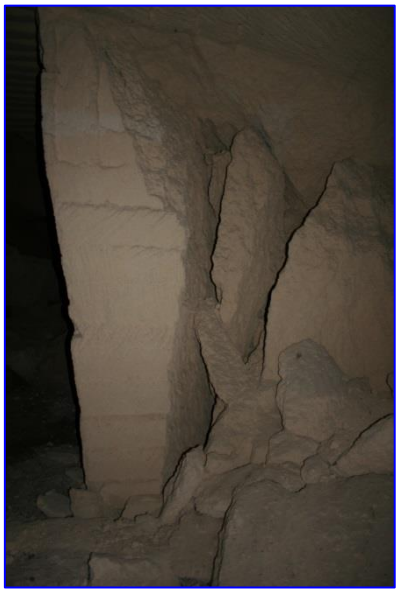
*photo: CARS*

# Altamura





*photos: CARS*



## Main priority: knowledge about the cavity location

Inventory is crucial, being the first step toward knowledge of the territory, including what is at the surface, and what is below the ground

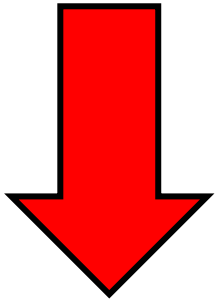
Inventory, through the Register of artificial cavities

CATASTO DELLE GROTTE
E DELLE CAVITÀ ARTIFICIALI

Progetto per l'attuazione della
Legge Regionale 4 dicembre 2009, n.33
TUTELA E VALORIZZAZIONE DEL
PATRIMONIO GEOLOGICO E SPELEOLOGICO

## Absolute priority: knowledge of the cave survey

If we do not know where the underground voids are, it is not possible to start any action of recovery, valorization, and safeguard



Speleological survey

Pu.40

GRUPPO SPELEOLOGICO PUGLIESE
BARI

# GRAVE DI PACIUDDO

La grave si trova a circa 2 Km da Cassano-sulla strada per Acquaviva detta Fonti, è profonda m. 85 ed ha diverse diramazioni ampie.

L'esplorazione non è stata completata per mancanza di mezzi - (canotti).

Rilievo eseguito con bussola Richter dal geom. Fortunato e da DeTaquila.

BARI 1-7-62

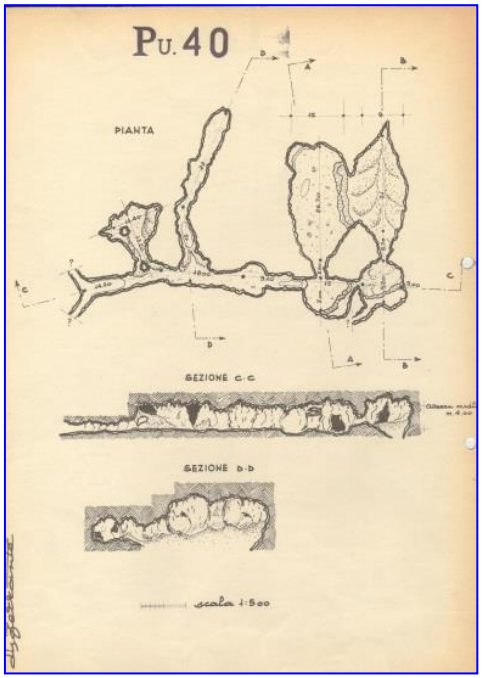
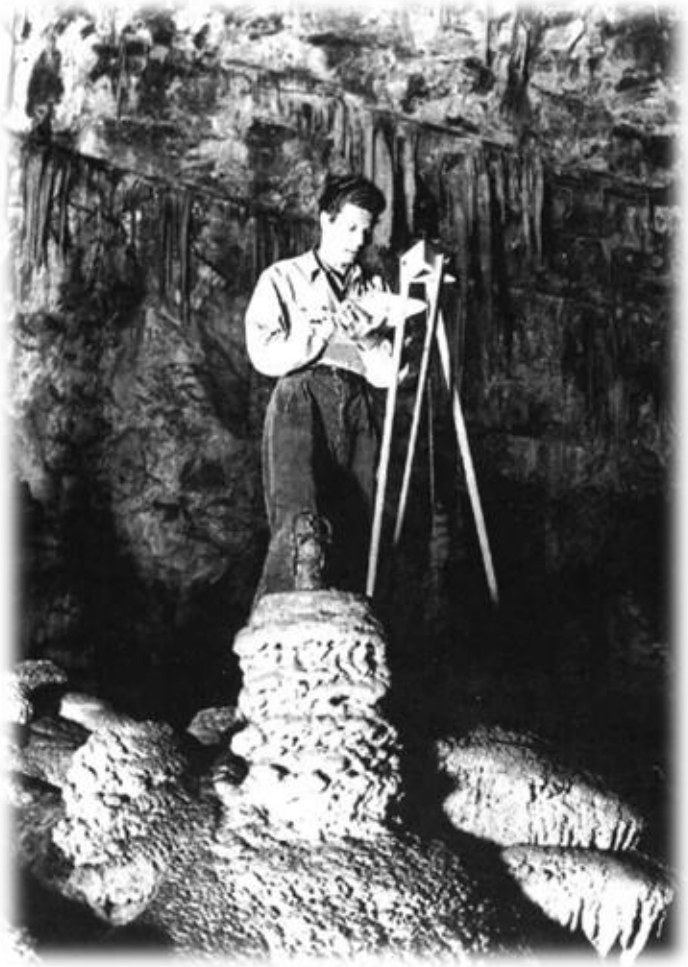
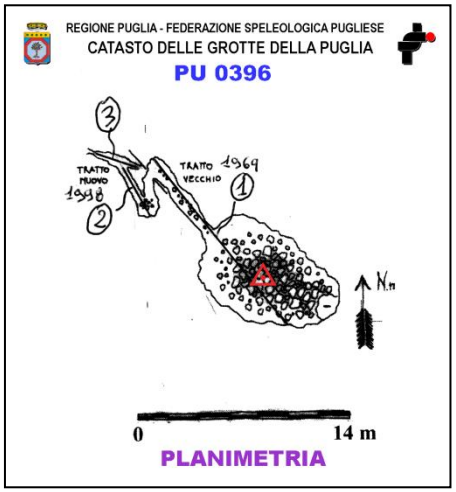
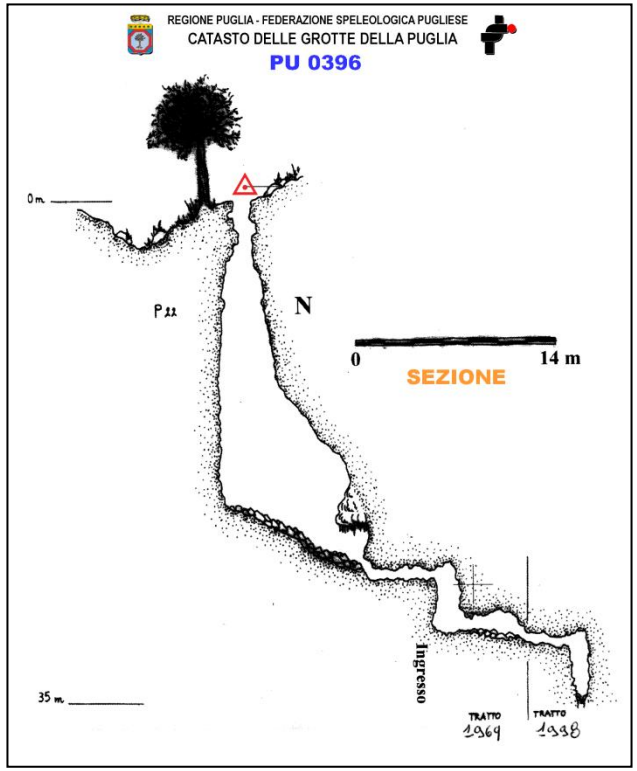



photo:archive CARS

centro altamurano ricerche speleologiche
CARS






- **Historical importance**
- **High technical and graphical ability (at the time)**
- **Limits of precision (elevation, direction, etc.)**
- **Surveys NOT realized for scientific or engineering aims**

PocketTopo 12:16

| From | To | Dist | Decl | Incl |
|---|---|---|---|---|
| 1830.2 | | 0.14 | 68.4 | 87.3 |
| 1830.2 | | 0.59 | 248.4 | -87.3 |
| 1503.50 | 1831.0 | 0 | 0 | 0 |
| 1831.0 | | 1 | 158.4 | 0 |
| 1831.0 | | 0.8 | 338.4 | 0 |
| 1831.0 | | 0.29 | 68.4 | 81 |
| 1831.0 | | 0.4 | 248.4 | -81 |
| 1831.0 | 1831.1 | 2.91 | 248.1 | 8.9 |
| 1831.1 | | 1 | 132.7 | 0 |
| 1831.1 | | 0.8 | 312.7 | 0 |
| 1831.1 | | 0.8 | 42.7 | -83.2 |
| 1831.1 | 1831.2 | 1.39 | 197.2 | -22.3 |
| 1831.2 | | 0.65 | 77.8 | 0 |
| 1831.2 | | 0.2 | 167.8 | 80.1 |

Menu

PocketTopo 12:16

1:750

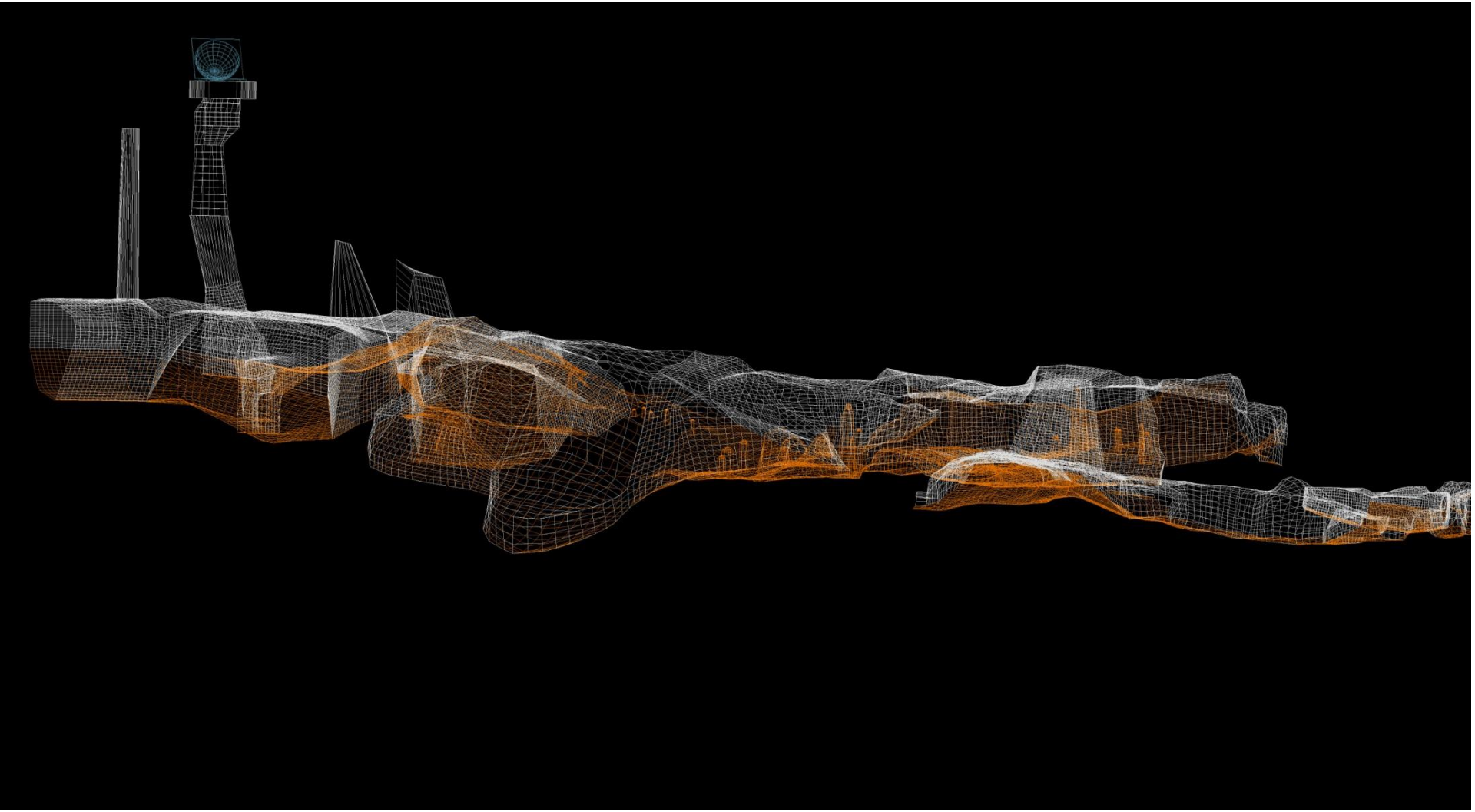
Menu

PocketTopo 12:17

1:300

Menu


Loch
File View Tools Help
425 m
426 m
423 m
419 m
417 m
418 m
416 m
408 m
415 m
Altitude
420 m
418 m
416 m
413 m
411 m
409 m
406 m
404 m
401 m
399 m
397 m
25 m



# Barletta

sinkhole in locality San Procopio
(May 3, 2010)

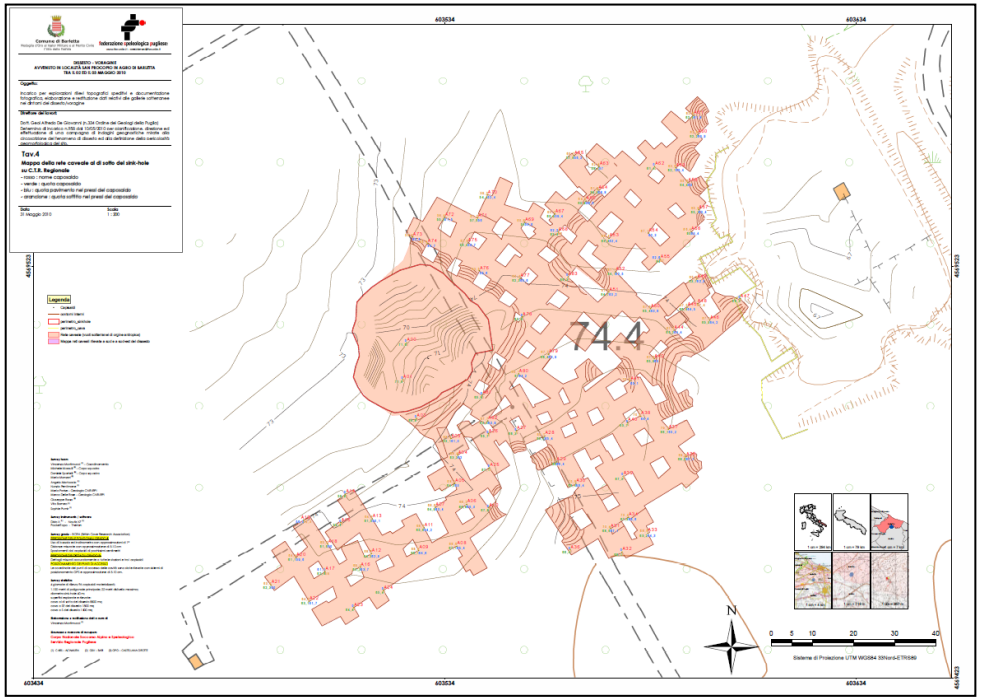
## Survey statistics

days of survey: 4;
96 benchmarks;
main survey line: 1.100 m;
max relief: 22 m;
sinkhole diameter: 36 m;
area of main quarry: 8500 sqm
quarry SE from sinkhole: 1800 sqm
quarry S from sinkhole: 1500 sqm

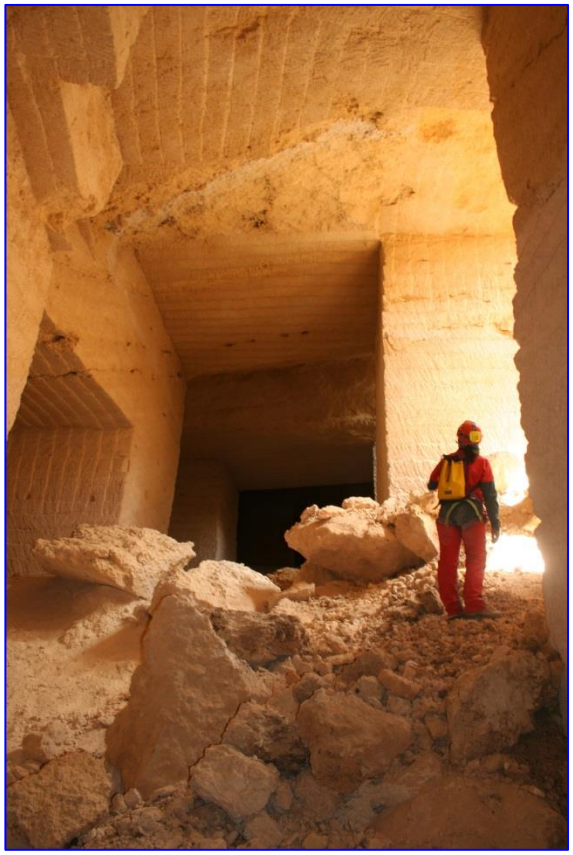
Exploration and surveys:

www.fspuglia.it
federazione speleologica pugliese

with the support of:

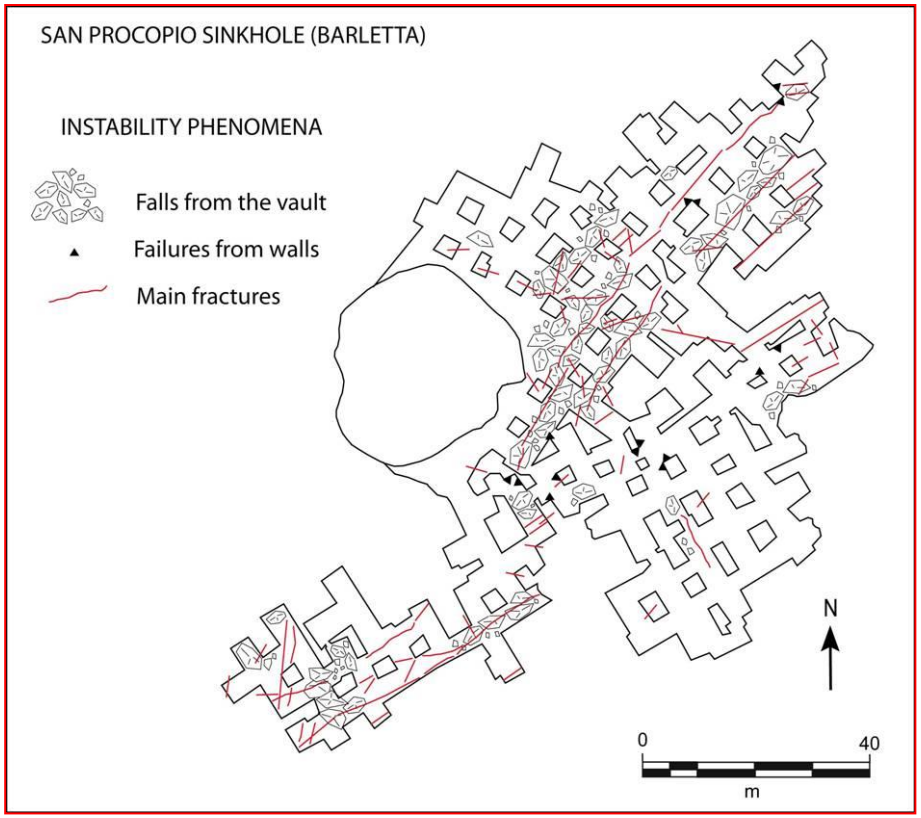


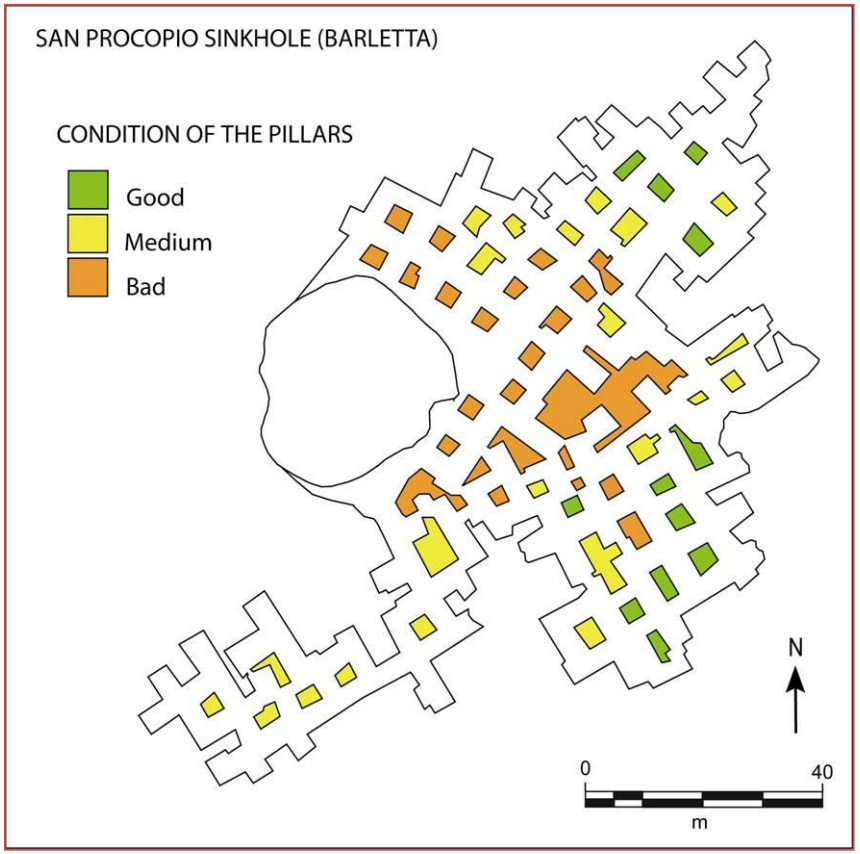
# Barletta



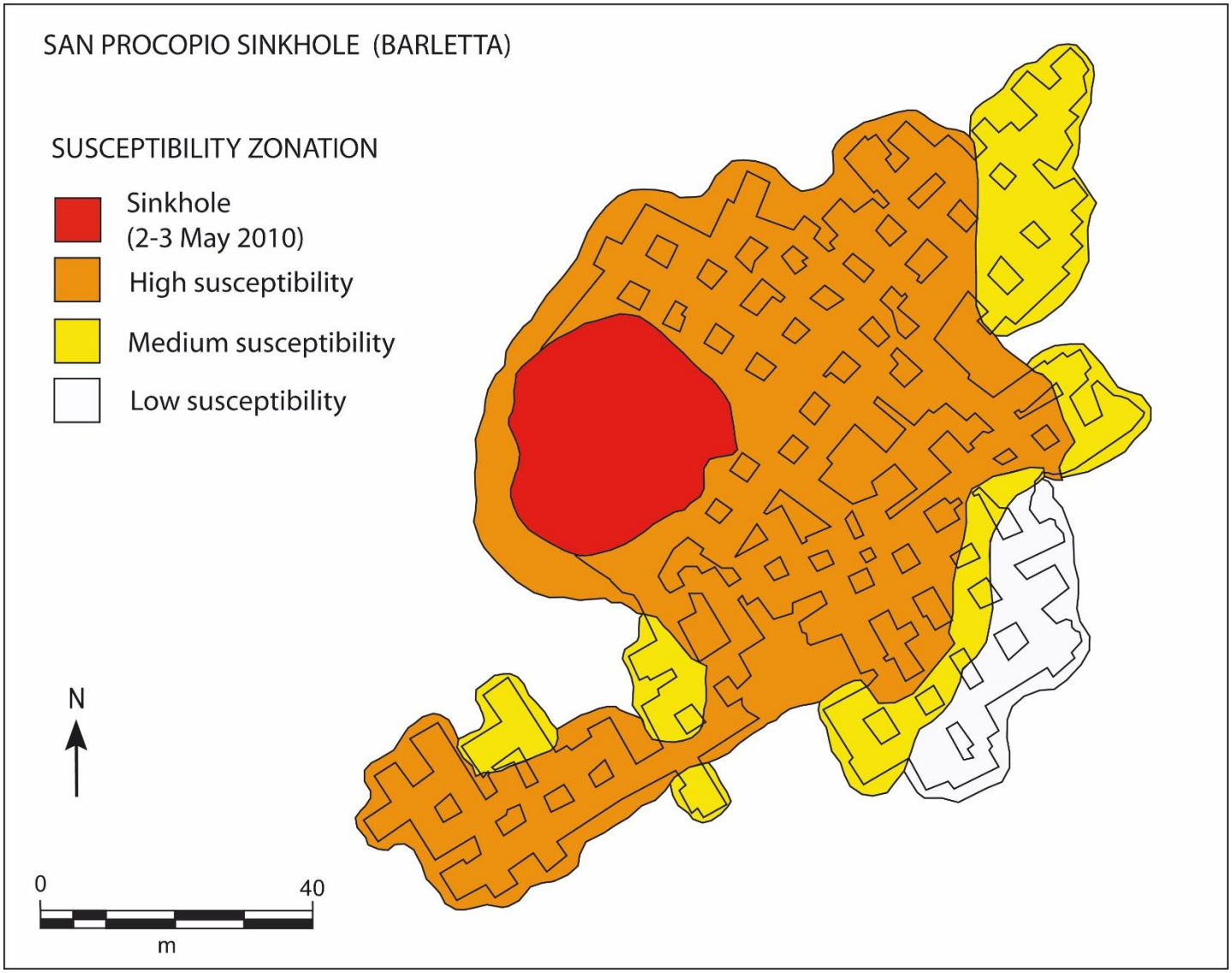
# Barletta

mapping



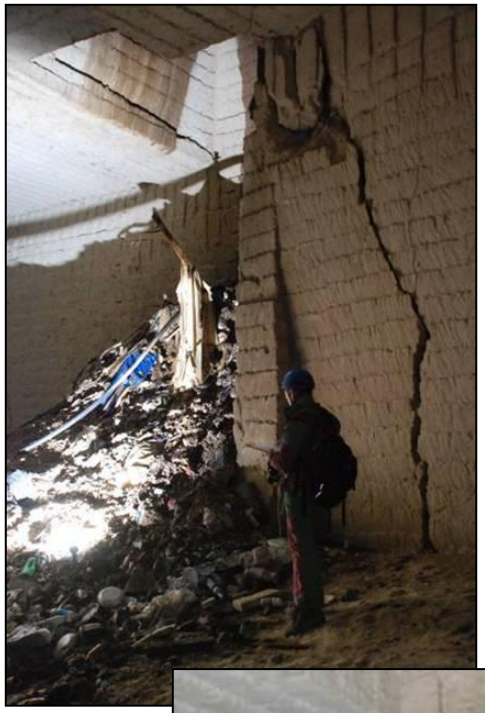



# Barletta


SAN PROCOPIO SINKHOLE (BARLETTA)
SUSCEPTIBILITY ZONATION
Sinkhole
(2-3 May 2010)
High susceptibility
Medium susceptibility
Low susceptibility
N
0
40
m

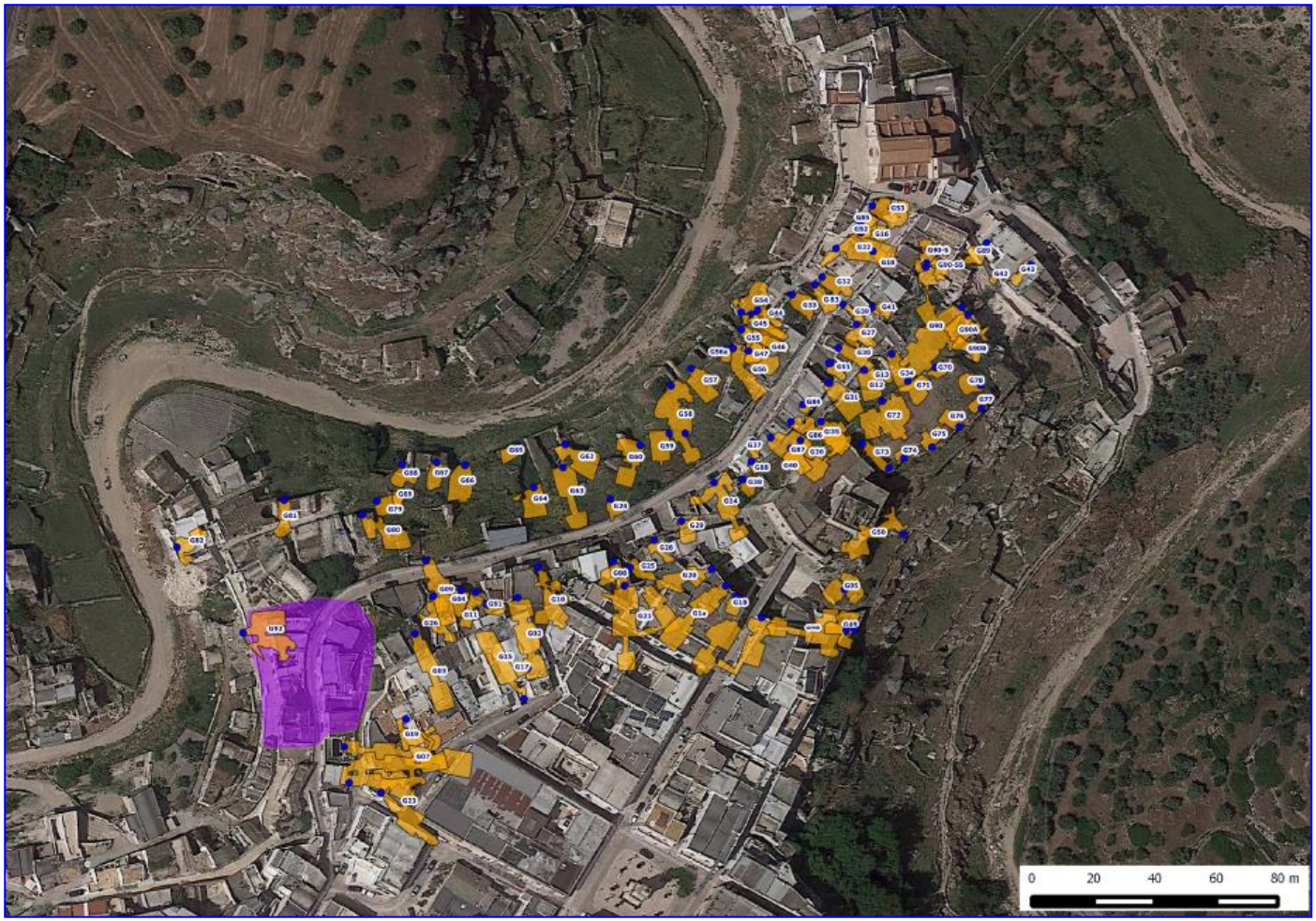
# FACTORS ACTING IN INSTABILITY OF UNDERGROUND WORKS

- ✓ **weathering** (water circulation and/or illegal discharge of liquid and solid wastes)
- ✓ changes in the **micro-climate** conditions of the cave (lack of ventilation)
- ✓ **loss of memory** of underground voids



# Interactions with the built-up environment


Topographic survey




Cavity distribution map.

1st step: knowledge of cave development and distribution.

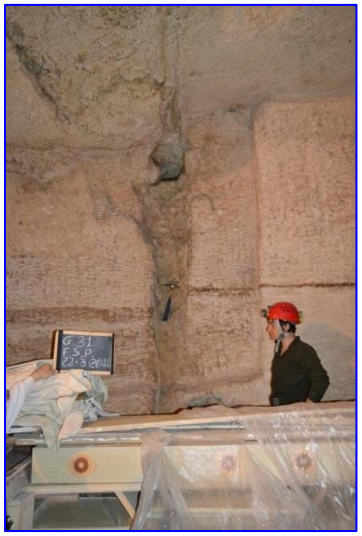
# How to “fill” the survey?

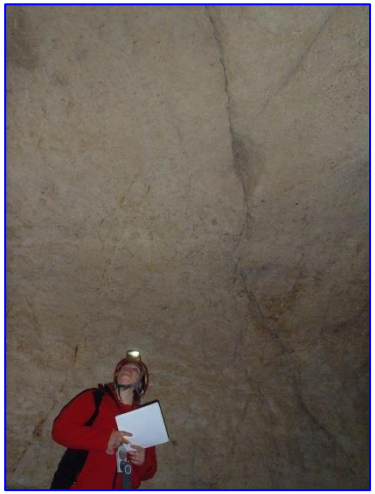
## What are the elements to consider for a preliminary assessment of the susceptibility to sinkholes?

- presence of cracks;
- presence of open joints;
- identification of the discontinuity sets;
- water infiltrations;
- para- or pseudo-karst cavities;
- deformations of the walls;
- weathering;
- unstable blocks;
- fallen blocks;
- wastes;
- instability in anthropogenic elements;
- works to stabilize or support;
- etc.

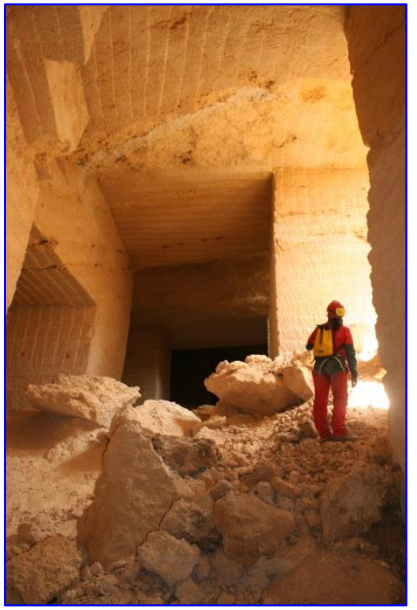
# Cracks

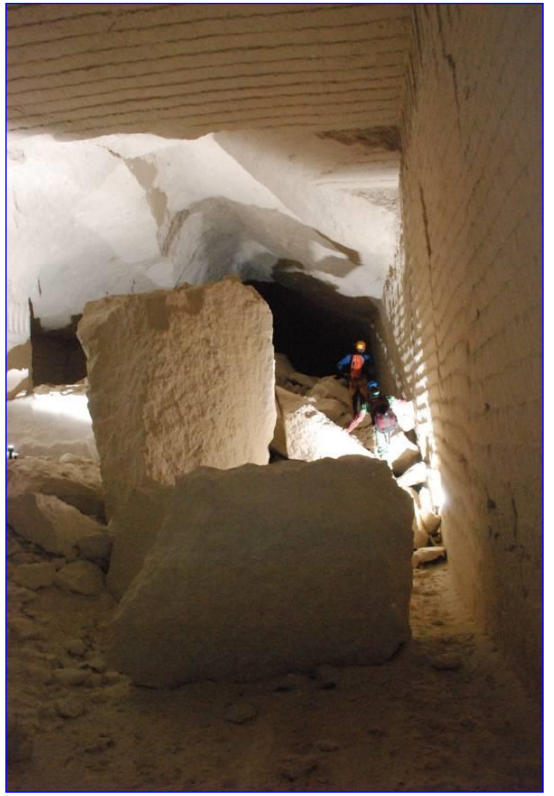




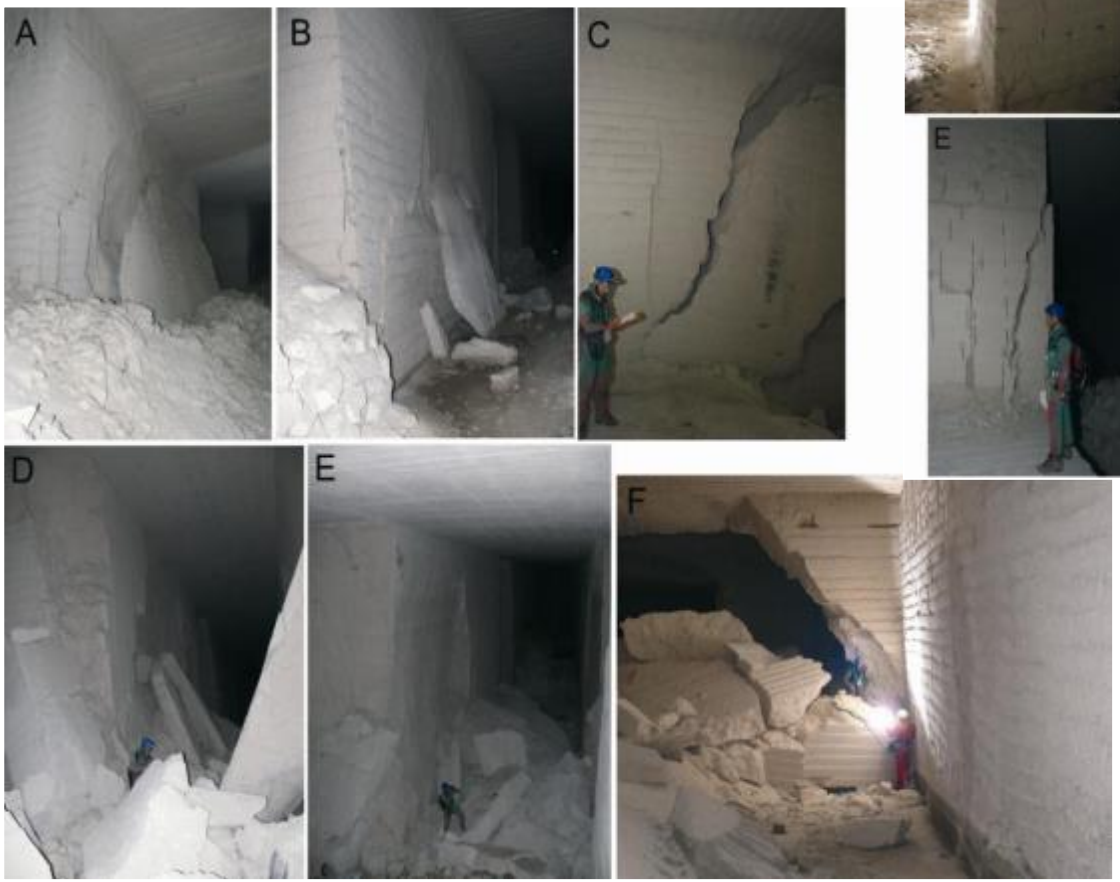



# Failures from the vault





Failures from the walls





Deformation at edges of pillars

Geomorphology 134 (2011) 132–143

Contents lists available at ScienceDirect

Geomorphology

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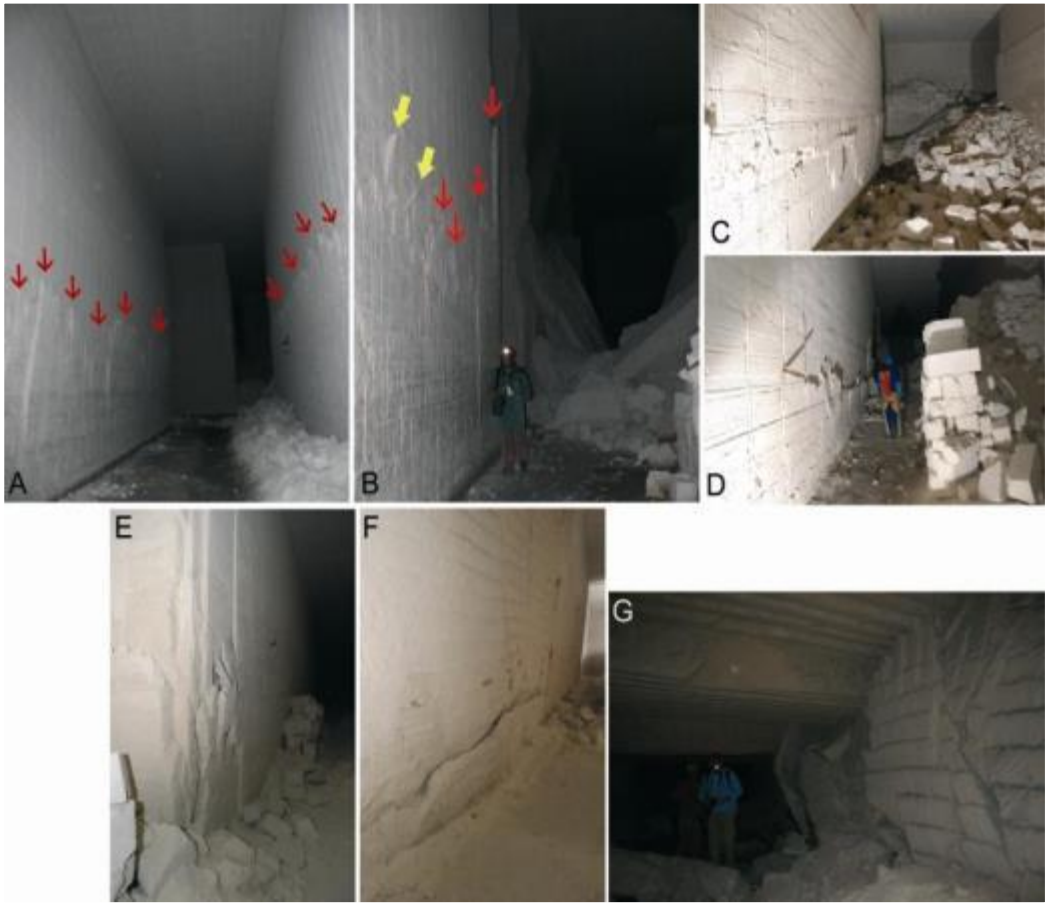
A preliminary analysis of failure mechanisms in karst and man-made underground caves in Southern Italy

M. Parise *, P. Lollino

National Research Council, Institute of Research for the Geo-Hydrological Protection, Via Amendola 122, 70126 Bari, Italy

*Parise & Lollino, 2011*




Deformation along the walls

Wedge extrusions

# Precursory signs

Geomorphology 134 (2011) 132–143

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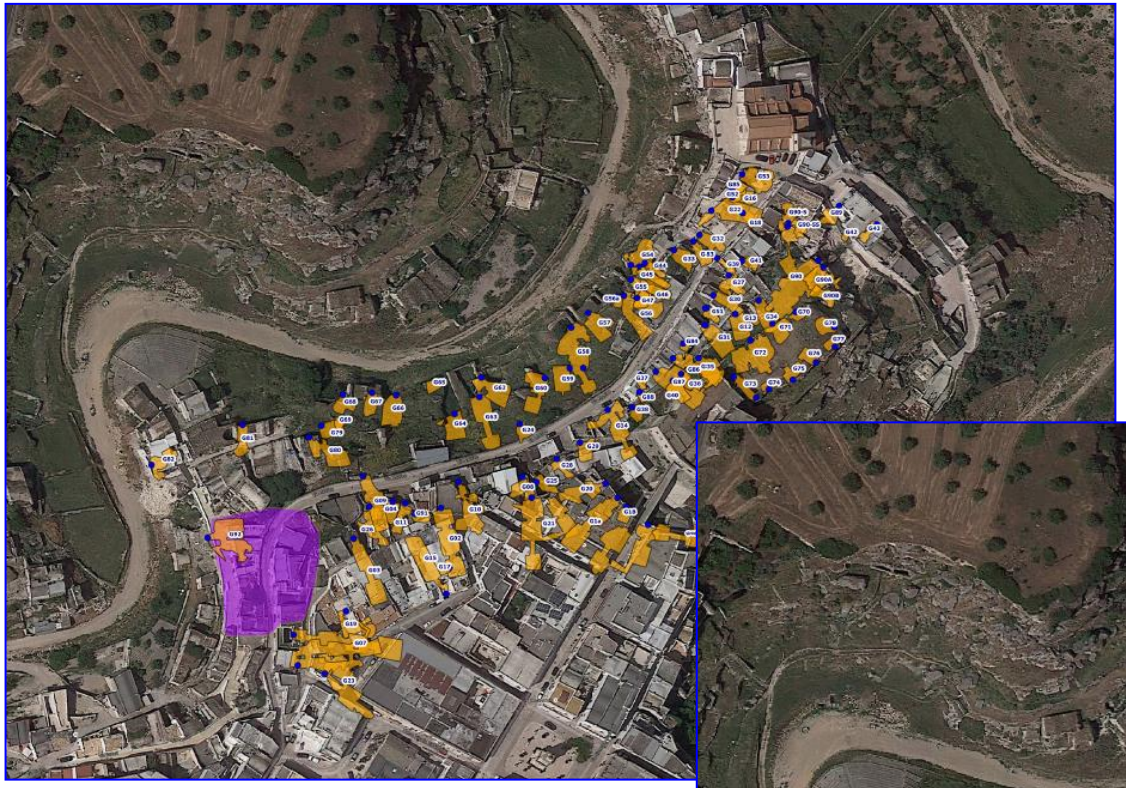
*Parise & Lollino, 2011*

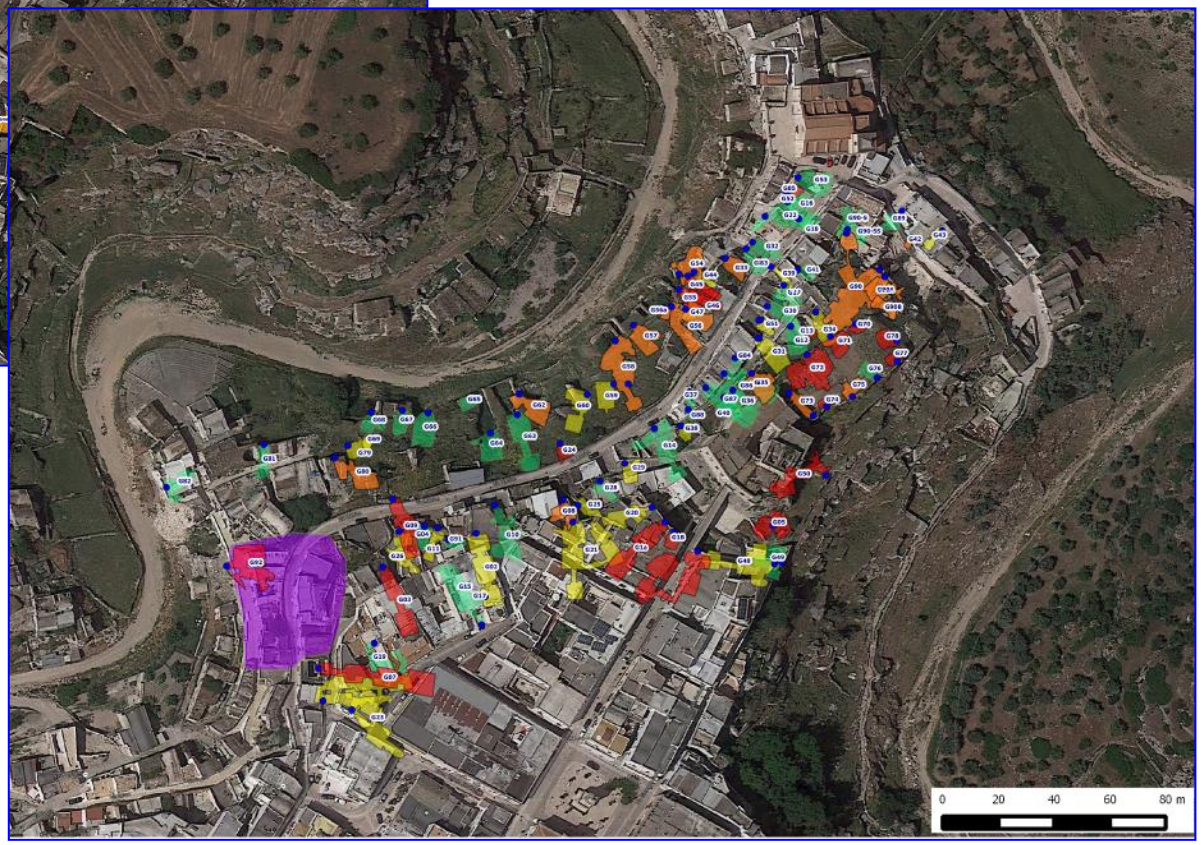
# mapping

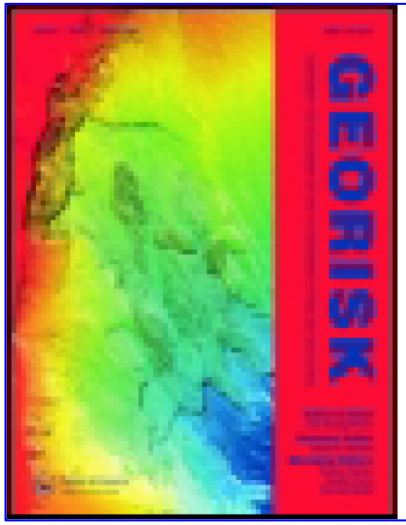

LEGEND
Falls from the vault
Falls from the walls
Fall deposits
Debris material
Fracture
Scarp
Deformation
Wastes
Downhill sector
(arrows point to lower elevations)
High passage
Calcarenite blocks
Pillar
Borehole
Liquid waste
SUSCEPTIBILITY
Low
Mean
High
Very high
B 12
B 11
N
0
10
m



Cavity distribution map

Map of the susceptibility to collapse






**Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards**

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ngrk20

# A procedure for evaluating the susceptibility to natural and anthropogenic sinkholes

Mario Parise[a]

[a] Institute of Research for Hydrological Protection, National Research Council, Bari, Italy

Published online: 22 Jun 2015.

Procedure for the **evaluation of the susceptibility to sinkholes**

- Cave location
- Typology of the cavity
- Speleological survey
- Geo-structural survey
- Identification of instability features
- Weathering
- Preliminary zonation
- Stability charts
- Lab analysis + monitoring
- Stability analysis (2D, 3D)

# Stability assessment in underground caves

Three methodologies

Heuristic methods

Analytical methods

Numerical methods

Isabella Serena Liso

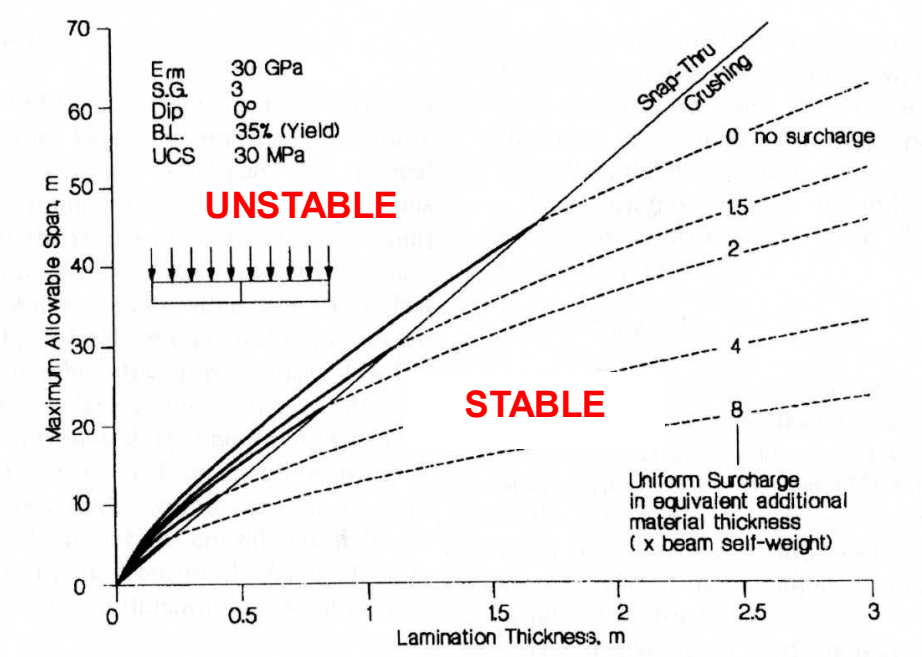
Piernicola Lollino

# Stability assessment in underground caves

## Heuristic methods

Abacus showing stable or unstable cave conditions, based on the combination of:

- cave geometry,
- geo-structural data, and
- rock strength parameters .

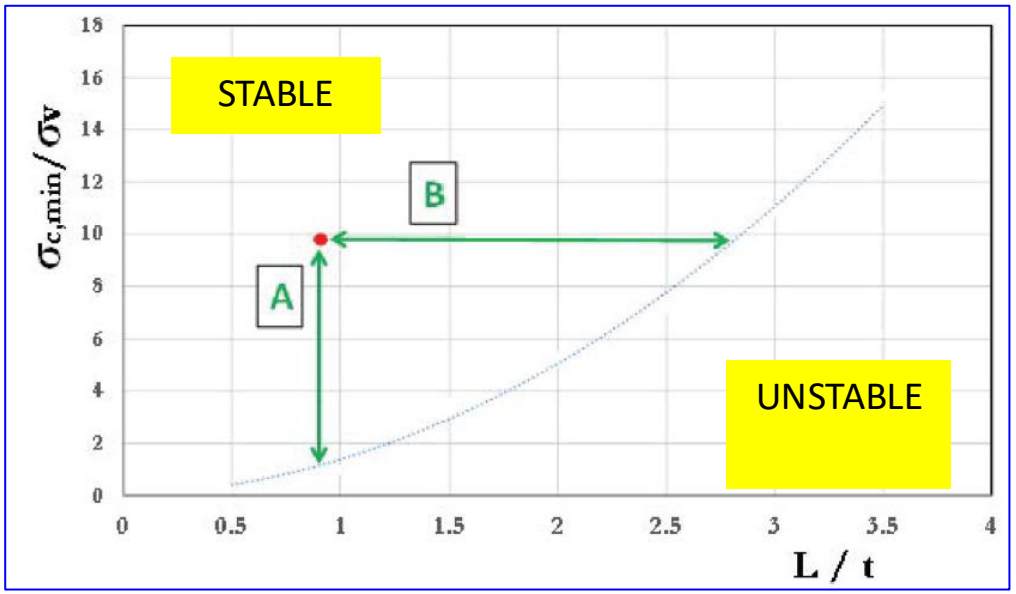


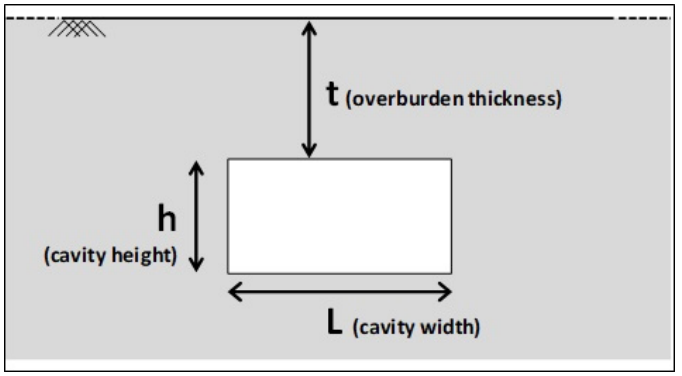

DIEDERICHS & KAISER, 1999

Drawbacks:

- ✓ uncertainties in the selection of the most proper approach (discontinuum or equivalent continuum), and
- ✓ presence of largely unpredictable karst features.

# *Building a stability chart through numeric multi-parameter analyses*




**$\sigma_{c,min}/\sigma_v$ :**
ratio between limit value of uniaxial compression strength at failure and pre-excavation lithostatic vertical load

**A** Computation of a safety margin for a failure mechanism at the vault: ratio $\sigma_c / \sigma_{c,lim}$

**B** Critical value of the ratio L/t

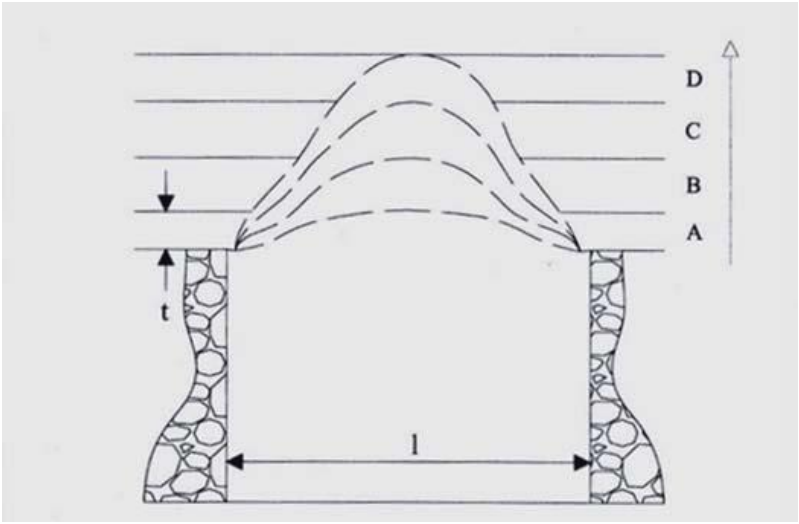
**L/t** = length/overburden

FIORE et al., 2018; PERROTTI et al., 2019, 2020

# Stability assessment in underground caves

Analytical methods

- Simplified computation of the limit conditions for the vault of a cavity under the hypothesis of a specified failure mechanism
- Estimate the limit values of stress in the rock mass by means of elastic solutions for problems with simple geometry
- Comparison with the rock mass strength




Beam theory applied to caves, and upward progression of failure (arch-shaped vault).

$$\sigma_{t,\max} = \frac{\gamma l^2}{2t}$$

OBERT & DUVALL, 1967

if $\sigma_{t,max} > r_t$

development of fissures

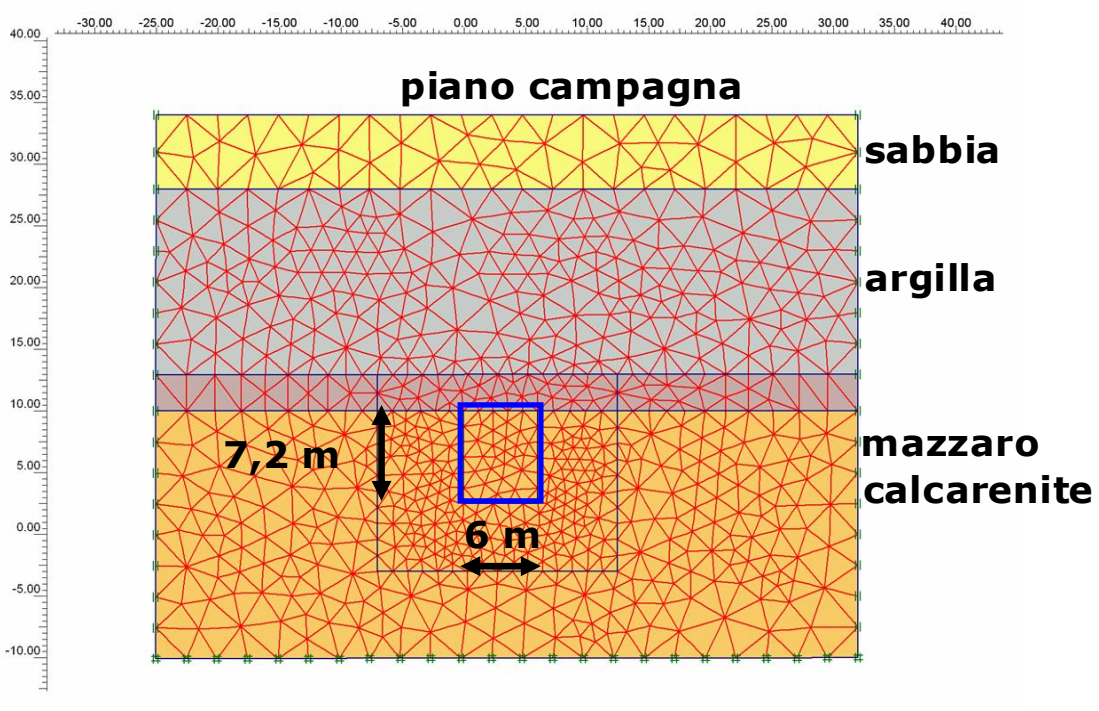
# Stability assessment in underground caves

## Numerical methods

Highly performant as a tool to investigate the stress-strain evolution of the rock mass around the cave.
Variations of equilibrium and the associated displacement field generated by loading or by a change of the boundary conditions can be correctly calculated

Simple elasto-plastic constitutive models (Mohr-Coulomb or Hoek-Brown failure criterion), within finite element analyses of underground caves

# Finite Element Model

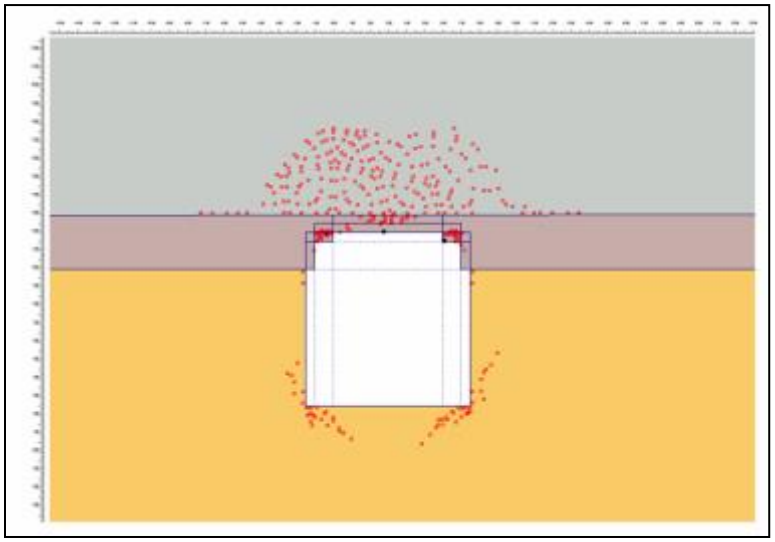



Mechanical properties of materials

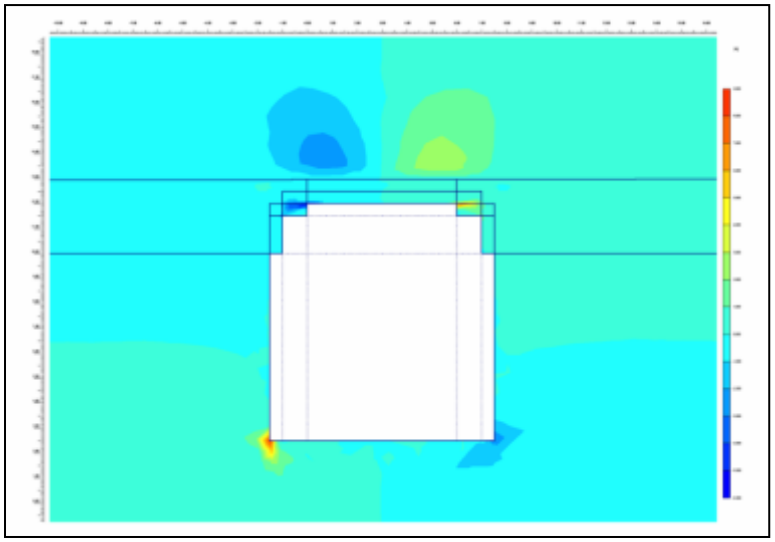
| | $\gamma$ (KN/m$^3$) | E' (kPa) | $\nu$' | c' (kPa) | $\varphi$' (° ) | $\sigma_t$ (kPa) | $\sigma_c$ (kPa) |
|---|---|---|---|---|---|---|---|
| *Sabbia* | 18 | 70000 | 0.3 | 0 | 28 | 0 | - |
| *Argilla* | 20 | 40000 | 0.25 | 15 | 20 | 0 | - |
| *Mazzaro* | 17.5 | 180000 | 0.3 | 360 | 33 | 300 | 2400 |
| *Calcarenite* | 15.5 | 100000 | 0.3 | 160 | 30 | 160 | 1400 |

# Finite Element Model

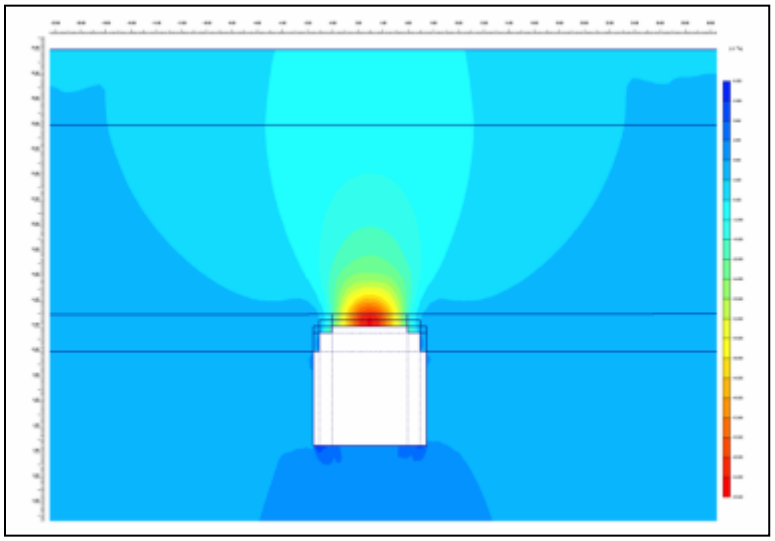
Increase of the cave size – 1st stage



Plastic points



Contours of shear strains



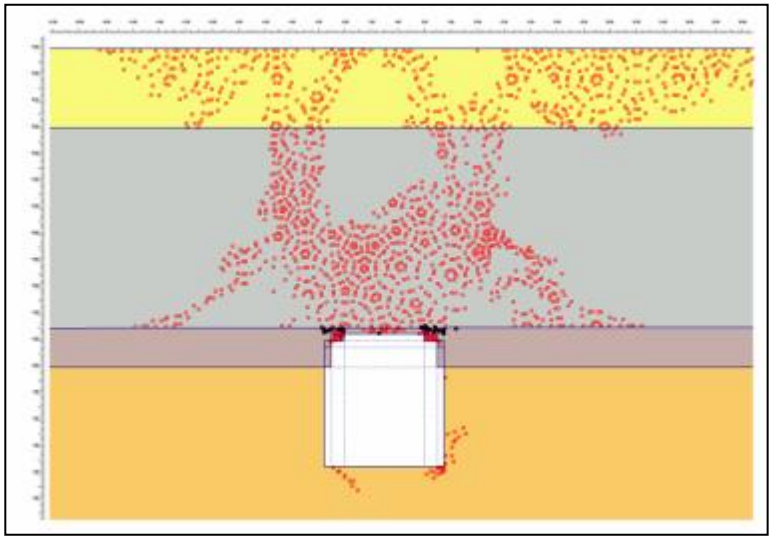
Contours of phase vertical displacements

*Parise & Lollino, 2011*

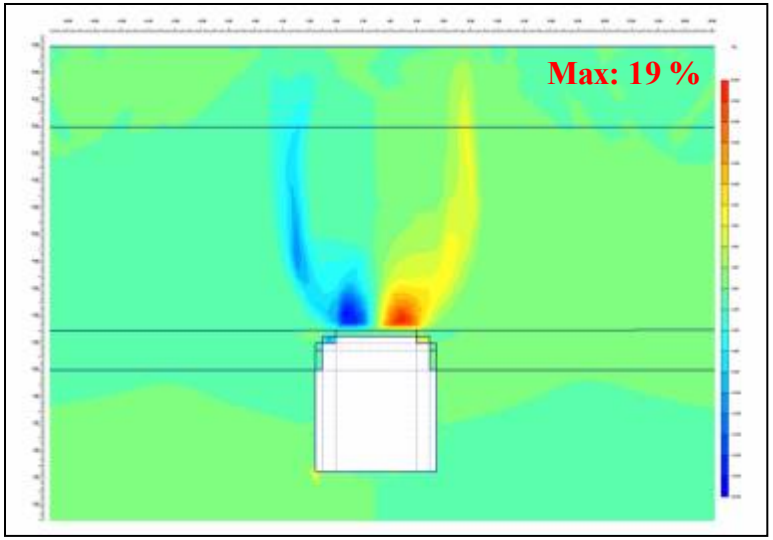
# Finite Element Model

*Parise & Lollino, 2011*

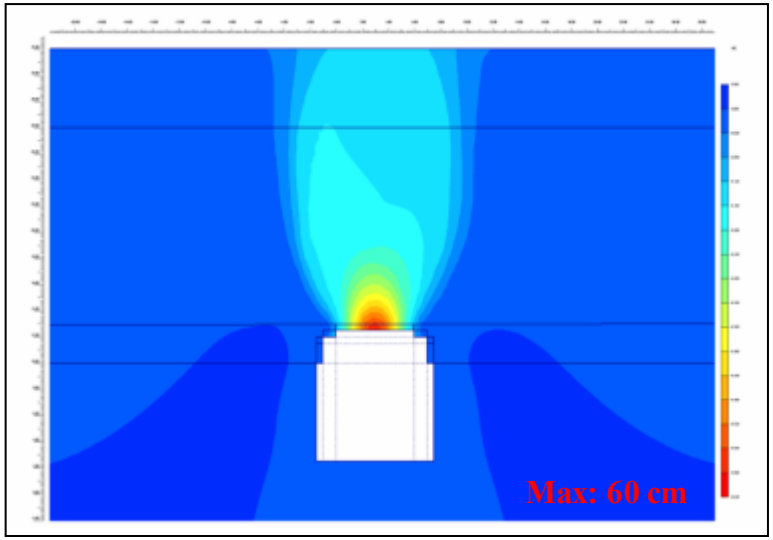
## Increase of the cave size – 2nd stage: failure



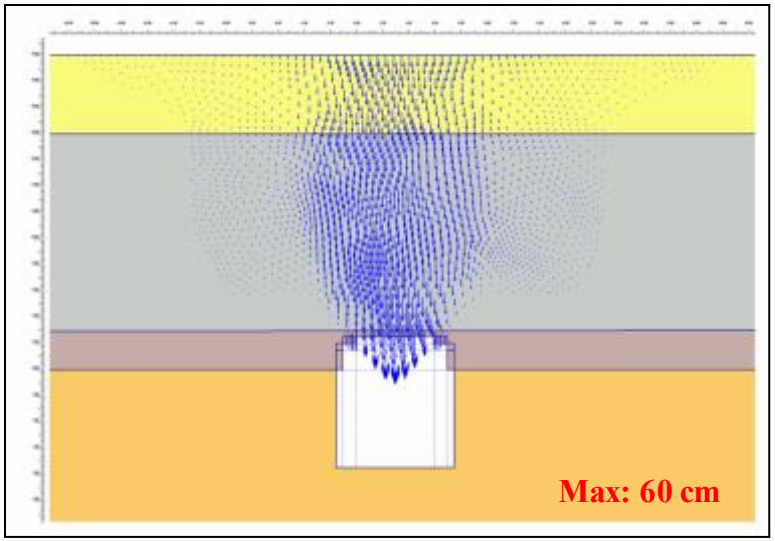
Plastic points




Contours of shear strains

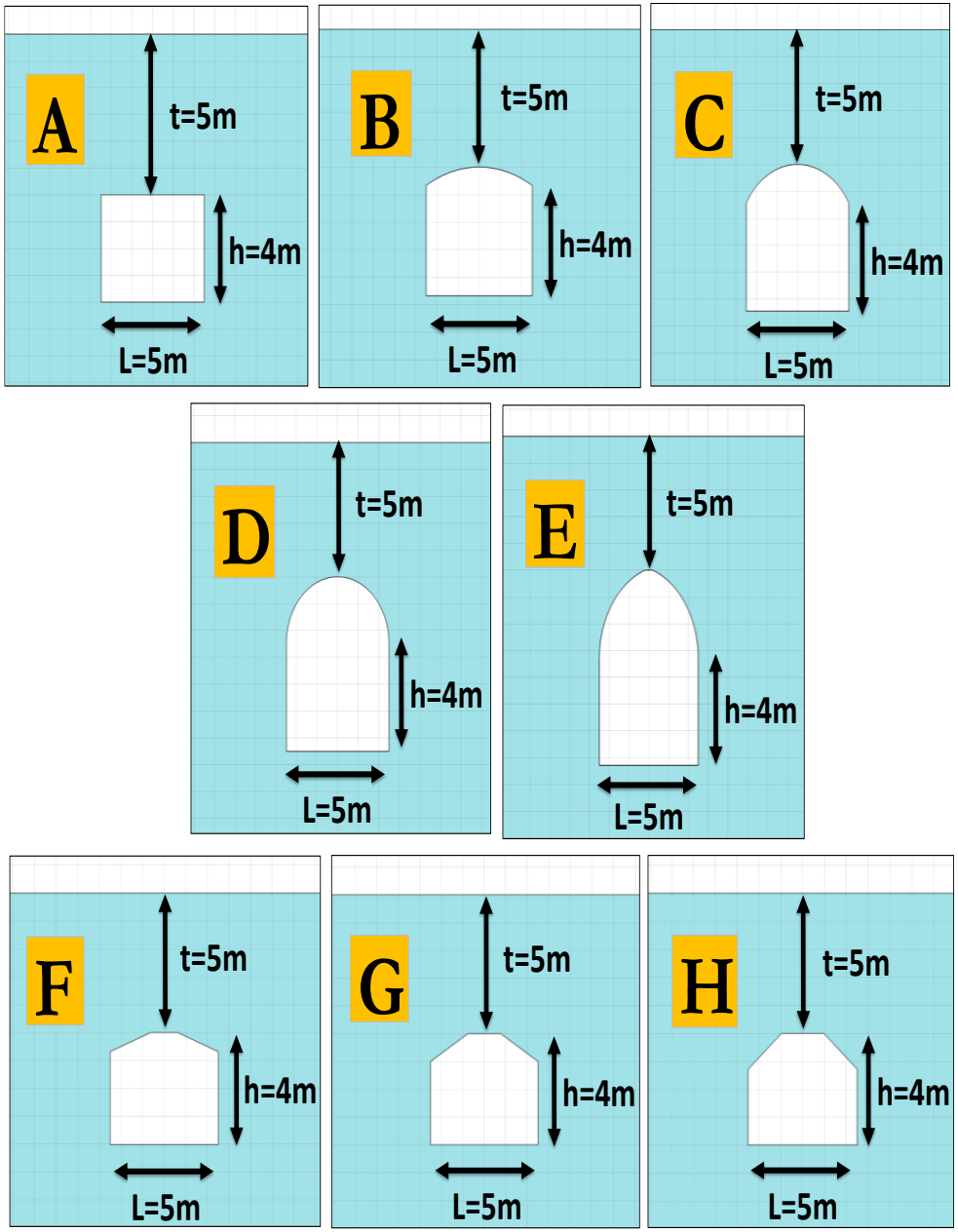


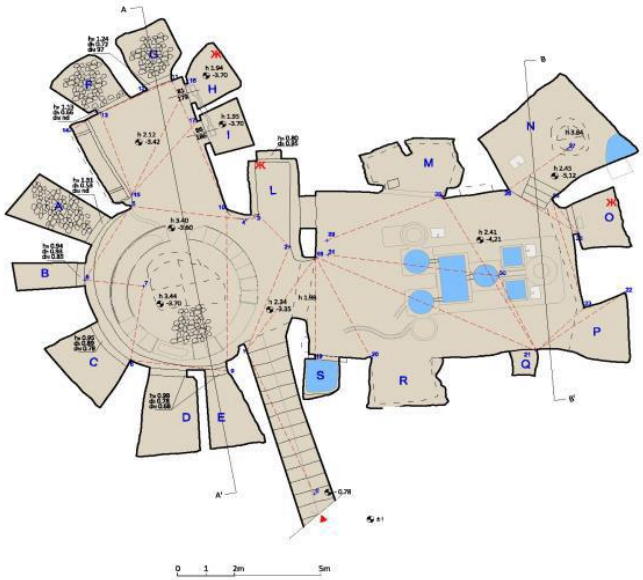

Contours of phase vertical displacements

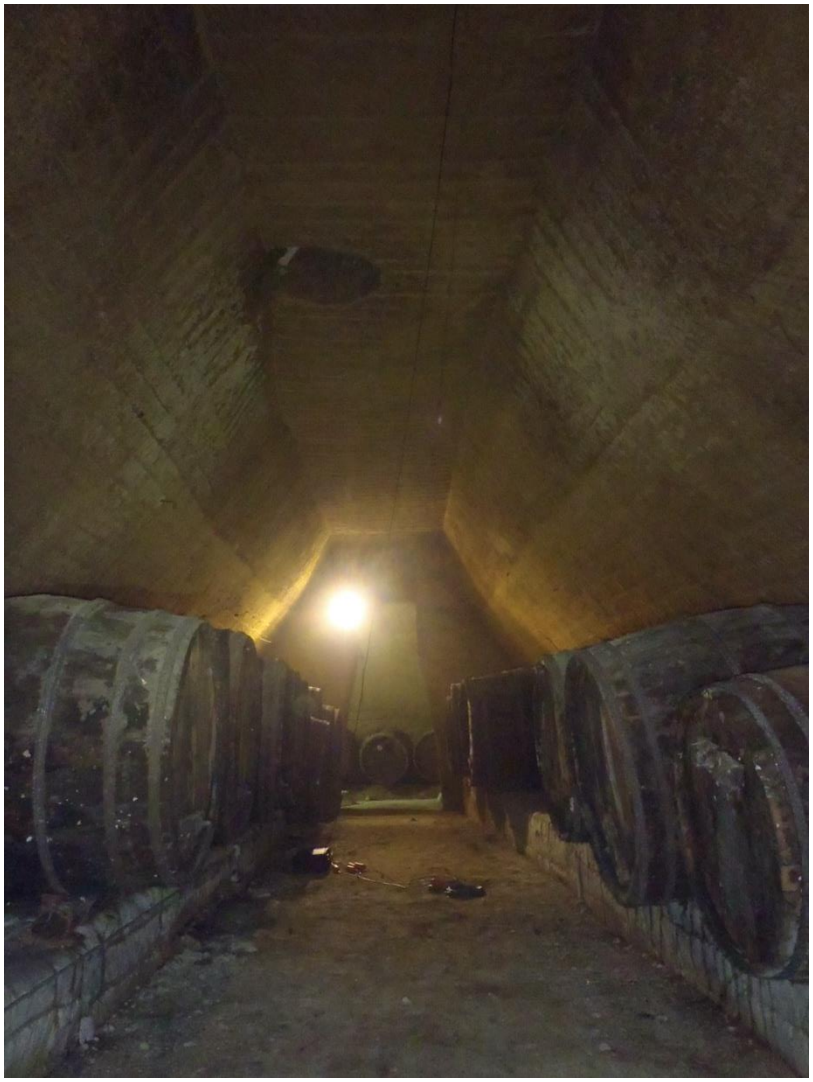



Phase vertical displacement vectors

# Single cavity: influence of the vault shape



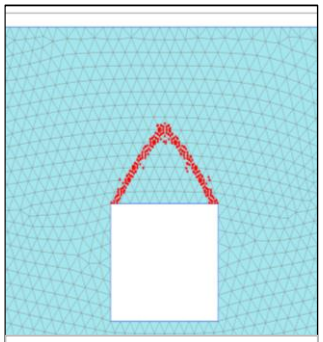





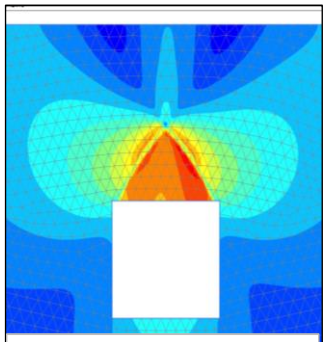
Calcarenite quarries with trapezoidal shapes
at Canosa di Puglia

# Single cavity: influence of the vault shape

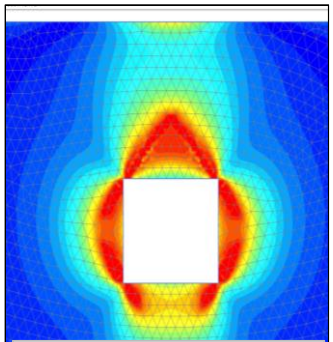
**A**



Punti plastici a rottura



Spostamenti verticali

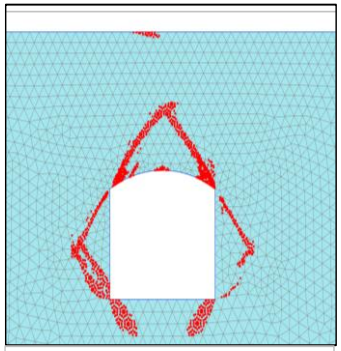


Tensione tangenziale relativa

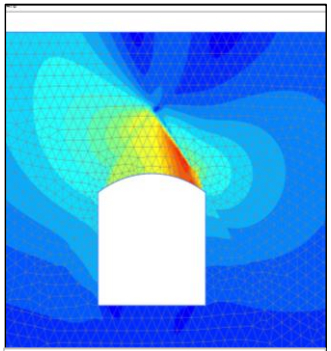
Resistenza a compressione monoassiale a rottura $\sigma_{c,lim}$ = 140 kPa.

Meccanismo ad arco (coinvolge circa metà spessore del tetto della cavità);
Spostamenti verticali elevati (generazione di un cinematismo).

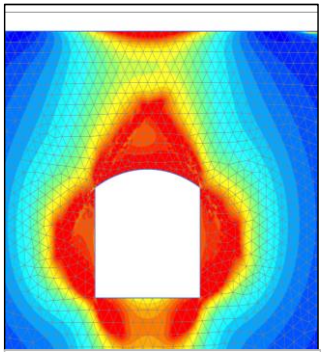
**B**



Punti plastici a rottura



Spostamenti verticali

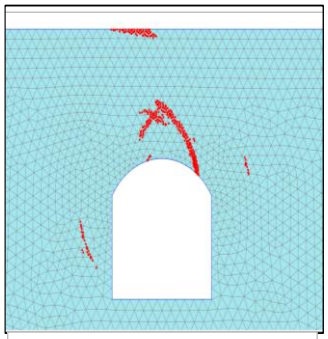


Tensione tangenziale relativa

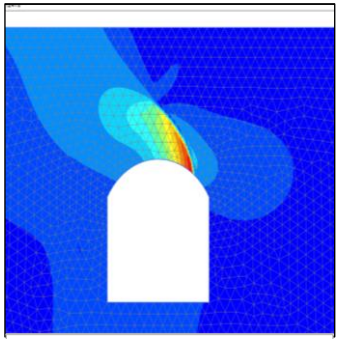
Resistenza a compressione monoassiale a rottura $\sigma_{c,lim}$ = 70 kPa.

Meccanismo ad arco (coinvolge circa metà spessore del tetto della cavità);
zone plastiche anche sulle pareti laterali della cavità.

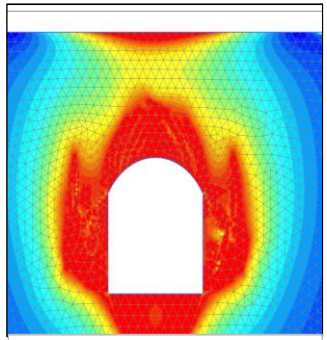
**C**



Punti plastici a rottura



Spostamenti verticali

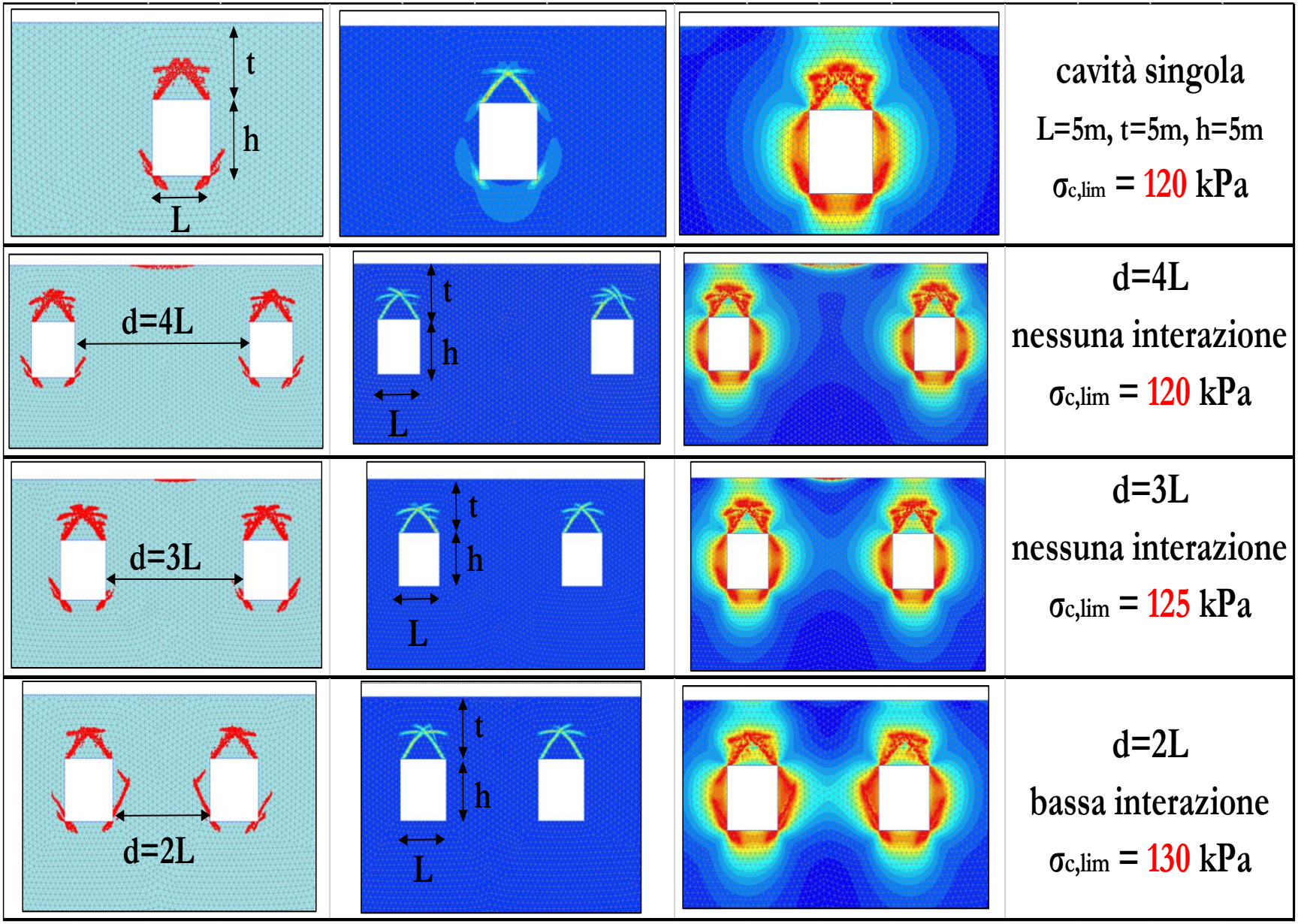


Tensione tangenziale relativa

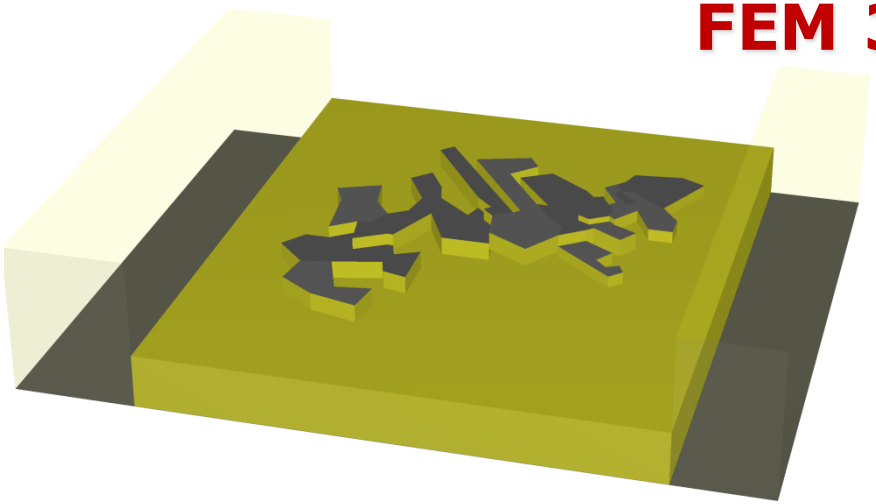
Resistenza a compressione monoassiale a rottura $\sigma_{c,lim}$ = 60 kPa.

Arco sopra la volta di dimensioni limitate;
distribuzione tensionale più uniforme nell'intorno della cavità.

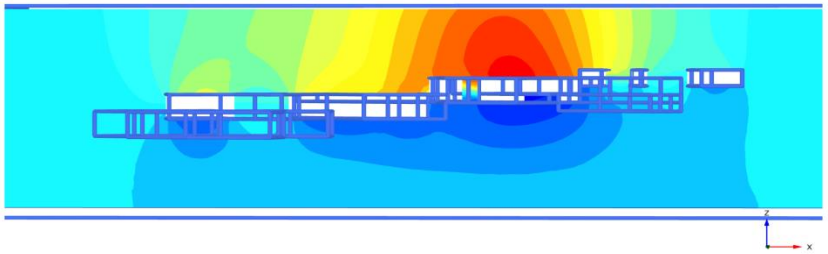
# Double cavities: influence of the distance among cavities



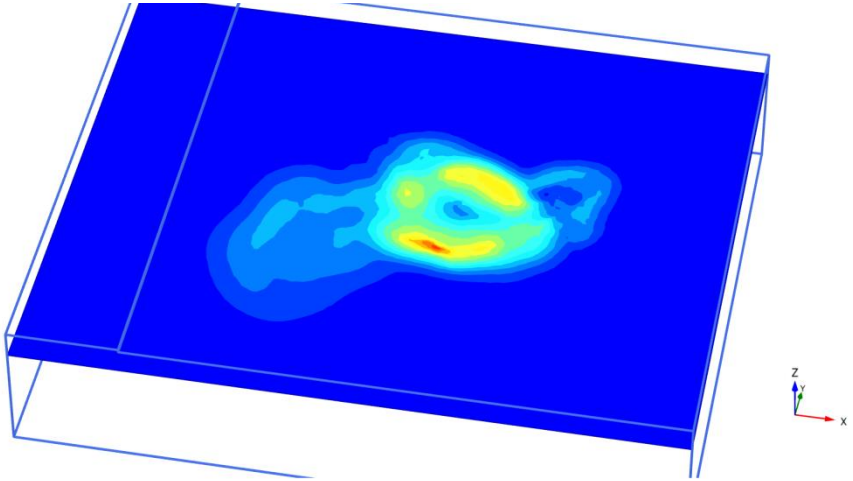
# FEM 3D MODEL (Plaxis 3D)

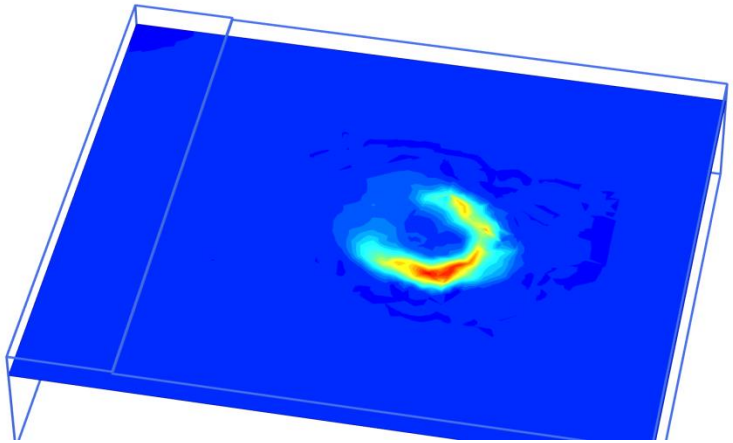


Prospective view of thre model



Vertical section: vertical displacements





Horizontal plain above the cave: deformations

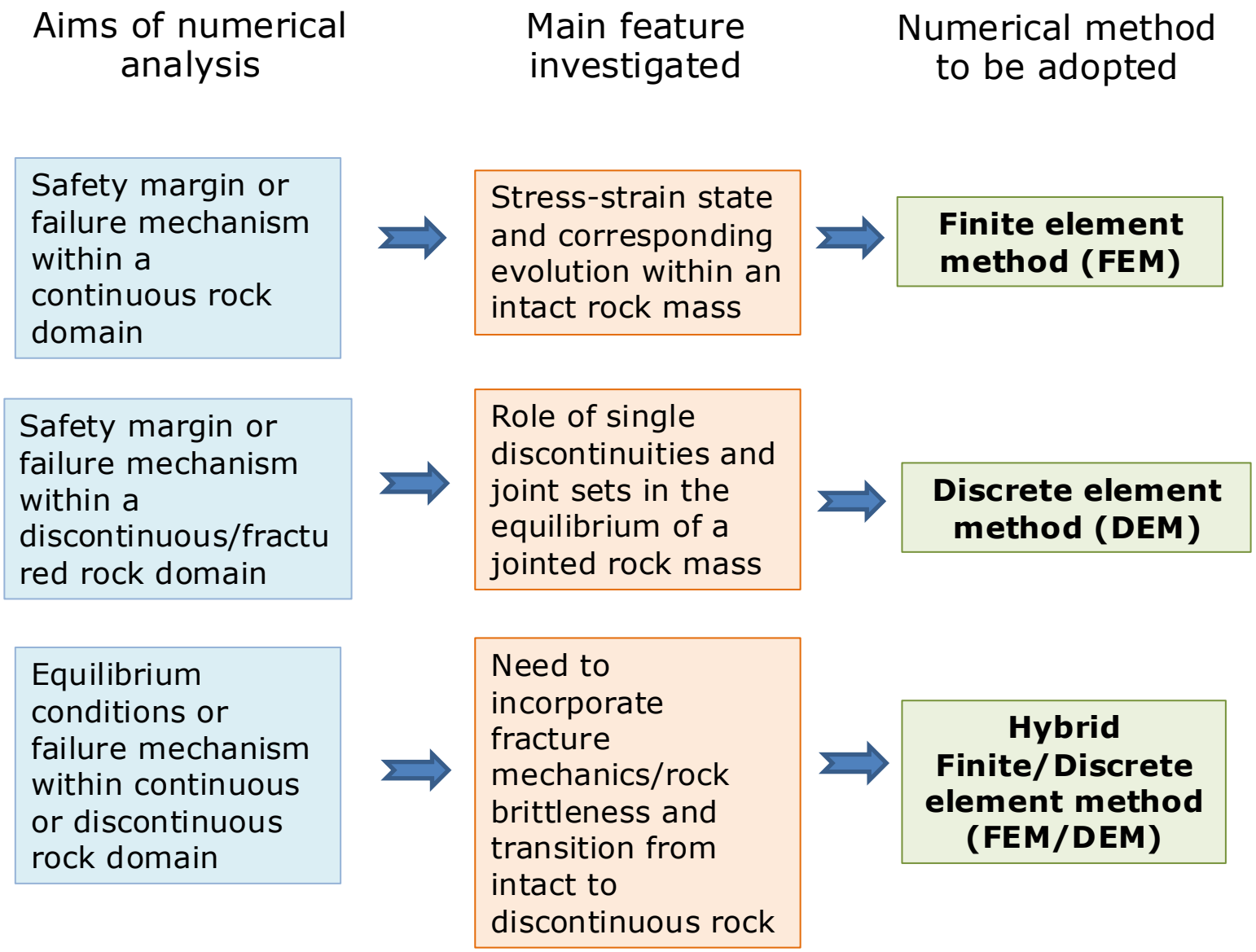
*Perrotti et al., 2018*
*Lollino et al., 2019*

## Hybrid models

Allow simulation of the rock stress-strain brittle behavior.

In a hybrid finite-discrete element method (FDEM), each discrete element is discretized into finite elements.

In this context, **continuum behaviour** is modelled through finite elements, while **discontinuum behaviour** is analyzed by discrete elements and transition from continua to discontinua is simulated through fracture and fragmentation processes.


Aims of numerical analysis
Main feature investigated
Numerical method to be adopted
Safety margin or failure mechanism within a continuous rock domain
Stress-strain state and corresponding evolution within an intact rock mass
Finite element method (FEM)
Safety margin or failure mechanism within a discontinuous/fractured rock domain
Role of single discontinuities and joint sets in the equilibrium of a jointed rock mass
Discrete element method (DEM)
Equilibrium conditions or failure mechanism within continuous or discontinuous rock domain
Need to incorporate fracture mechanics/rock brittleness and transition from intact to discontinuous rock
Hybrid Finite/Discrete element method (FEM/DEM)

# Conclusions

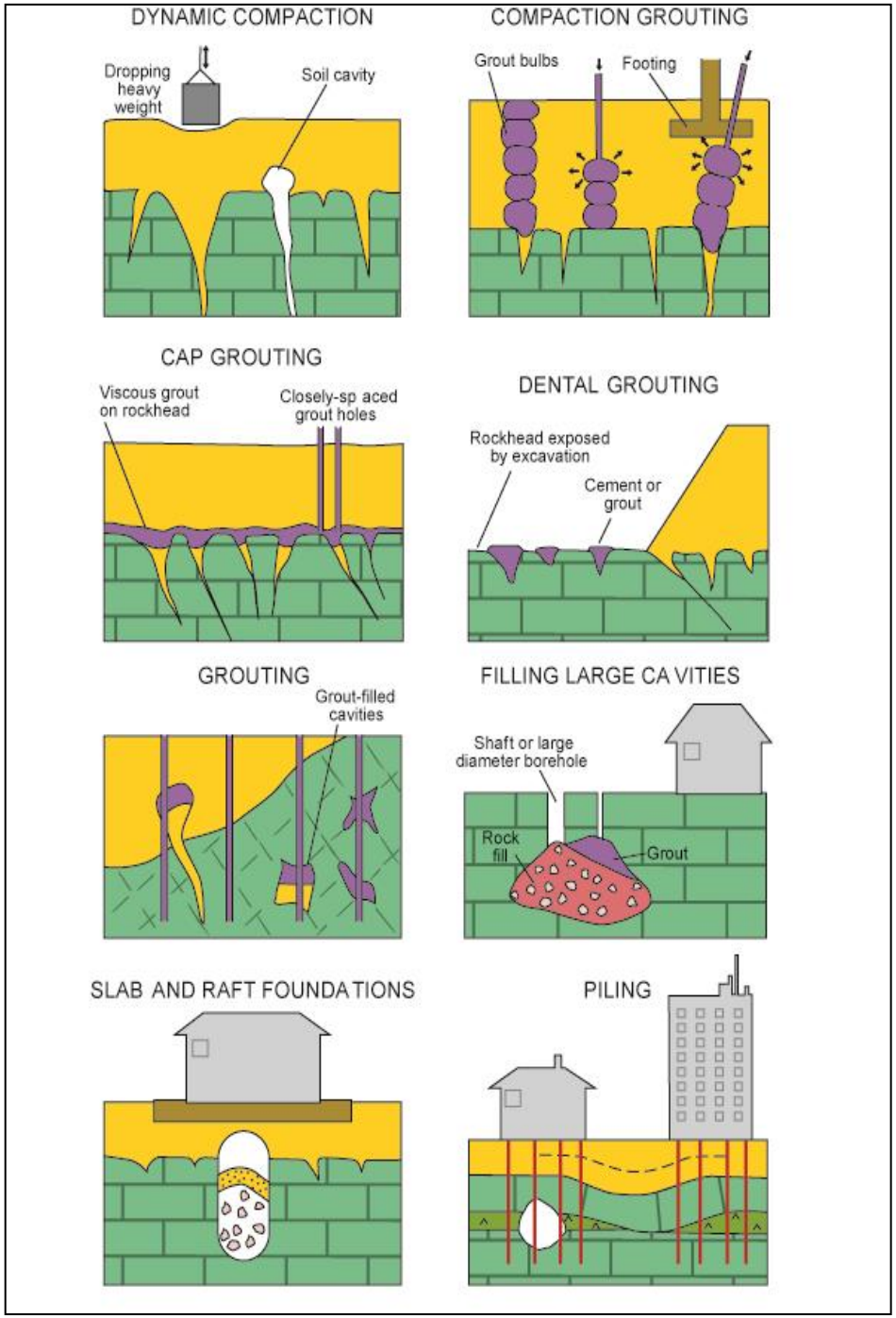
- To develop a numerical analysis aimed at investigating the equilibrium conditions or the failure mechanism of a rock mass surrounding an underground cave, a **proper numerical method** should be chosen in accordance to the rock mass conditions and the main features of the process to be explored.

- assessment of the failure mechanisms occurring in man-made caves within intact soft rock masses: the **finite element method** has proved to represent a reliable tool to detect the threshold conditions for the triggering of local or general failure mechanisms

**3-D models**

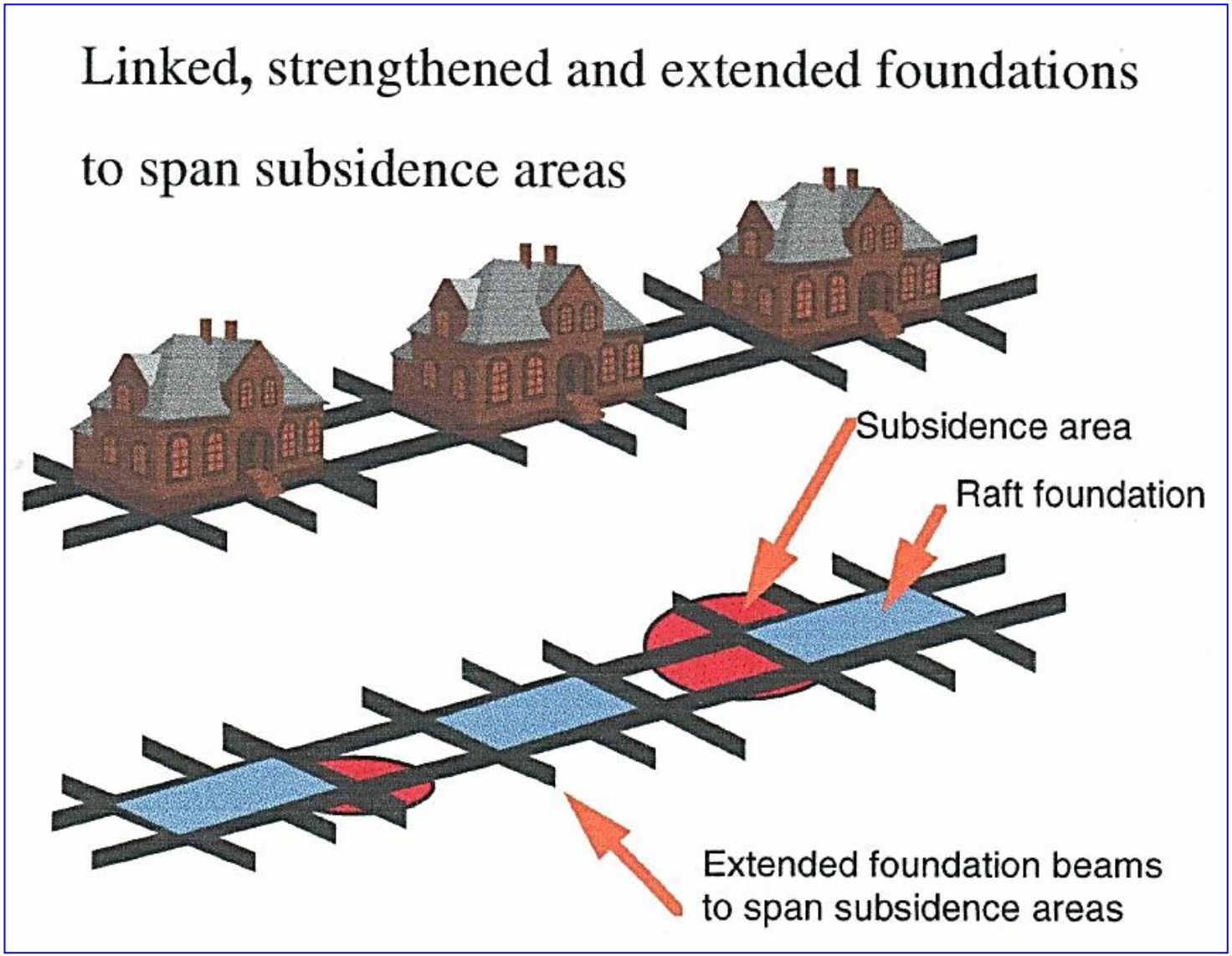
- natural karst caves: **discrete element method** is useful to detect the evolution of the stress-strain conditions leading to cave enlargement and final collapse

- in order to account for the fracture mechanics and the associated role of rock brittleness, more advanced **hybrid finite/discrete element methods** are nowadays available; specific attention must be provided to the eventual risk of mesh dependency of the numerical results




Potential measures aimed at reducing the activity of dissolution and subsidence processes or at protecting human structures incorporating special engineering designs

Gutiérrez, Parise, De Waele & Jourde, 2014, *A review on natural and human-induced geohazards and impacts in karst.* Earth Science Reviews 138, 61-88.




British Geological Survey, DFID, Tech. rep. WC/98/5: *Avoiding gypsum geohazards: guidance for planning and construction*

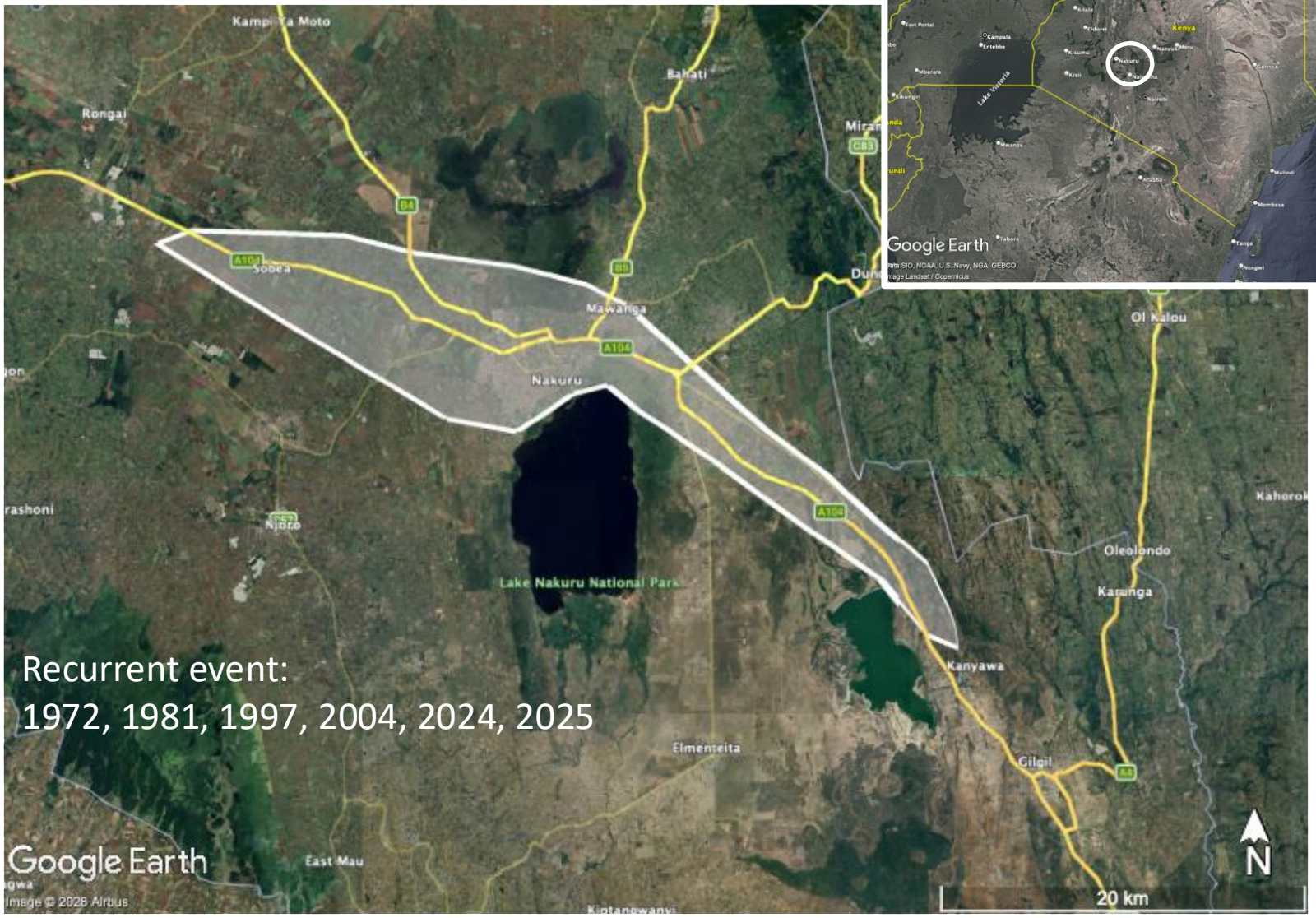
# Sinkholes in Kenya

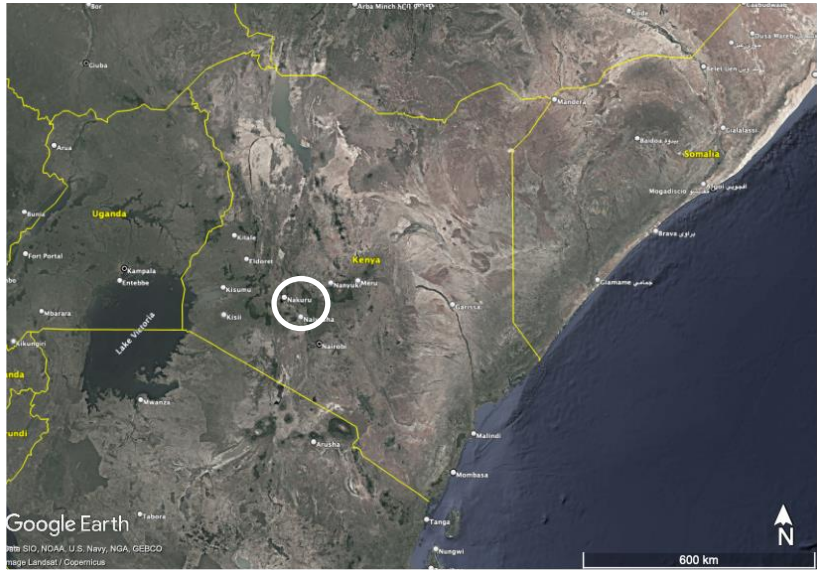
Zones with volcanic activity (lava tubes, gas, deep fractures).

Several areas interested:
**Nakuru**
**Baringo County** (Lake Baringo and Lake Bogoria)
**Maji Moto** (since 2013)
**Naivasha – Suswa – Mai Mahiu**
**Kedong Basin (Naivasha)**
**Gilgil (tra Nakuru e Naivasha)**
**Menengai**
**Olkaria/Naivasha**

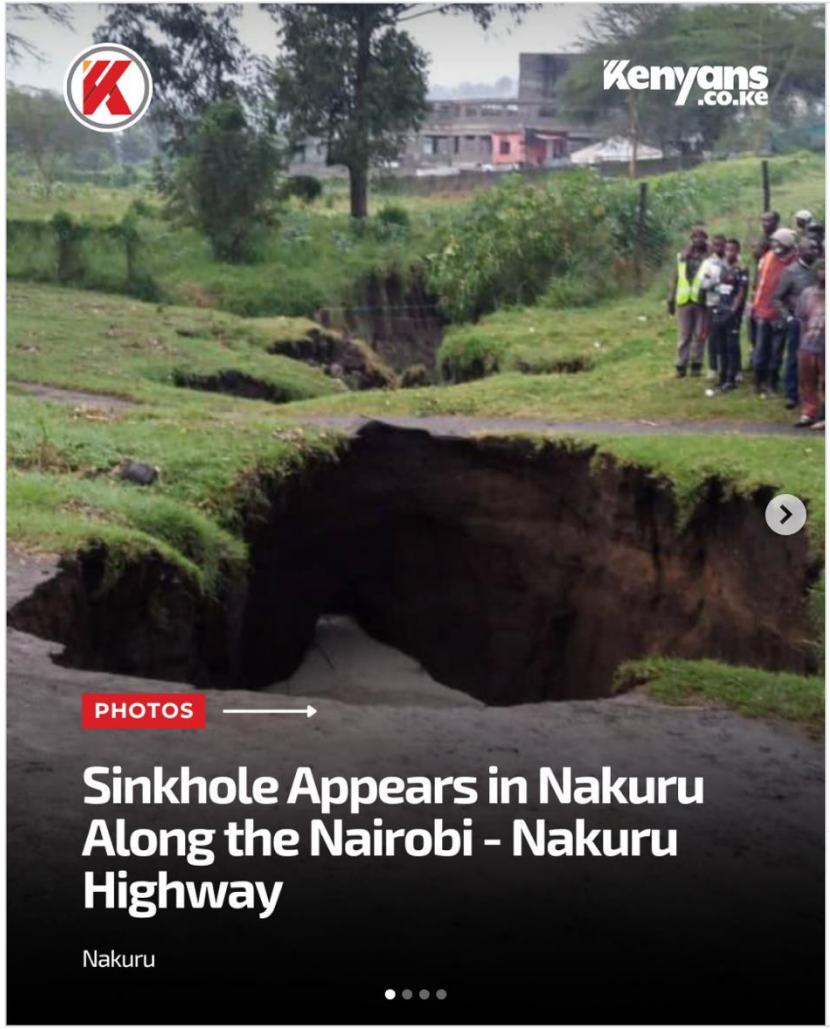
The sinkhole is on the road side at National Filling in London area of Nakuru Town West Sub-County.

**Nakuru** sinkholes



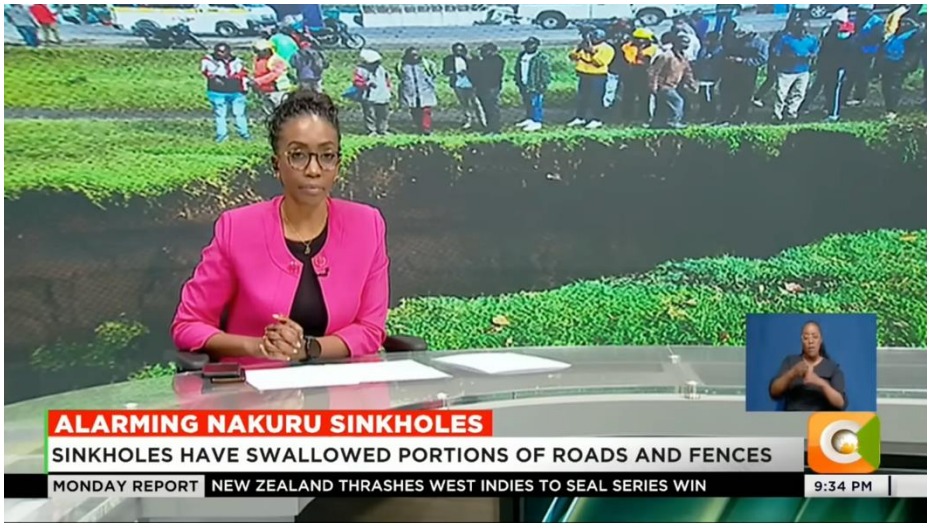
Instagram


Kenyans.co.ke
PHOTOS
Sinkhole Appears in Nakuru Along the Nairobi - Nakuru Highway
Nakuru


NGATA
KIAMUNYI
GIOTO
KAPTEMBWA
GILGIL
Nakuru
Lord Egerton Castle
Menengai crater
Nyonjoro
Baboon Cliff View Point
Beeston
Njoro
Lake Nakuru National Park
NYANDARUA COUNTY
NAKURU COUNTY
ALARMING NAKURU SINKHOLES
NAKURU RECORDS A SURGE IN SINKHOLES & GROUND FISSURES
MONDAY REPORT
TWO CHILDREN AGED 11 &12 ARRESTED FOR STEALING KSH 30,000 IN KIRINYAGA
9:37 PM

# Instagram


CONFRENCE
ACCOMMOD
COFFEE SHO
RESTAURANT
BUTCHERY
BAR
BASEMENT PA
AMPLE
PARKING


**Not a karst process**

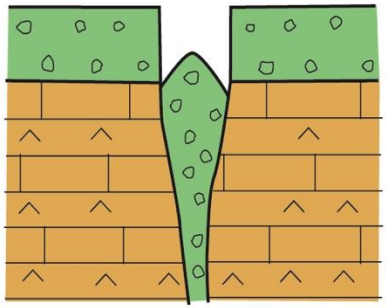
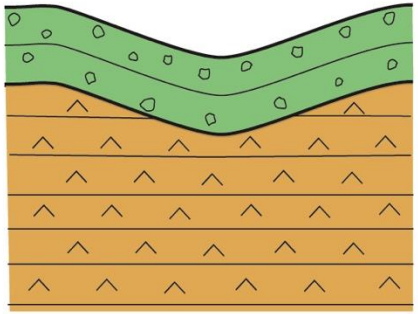
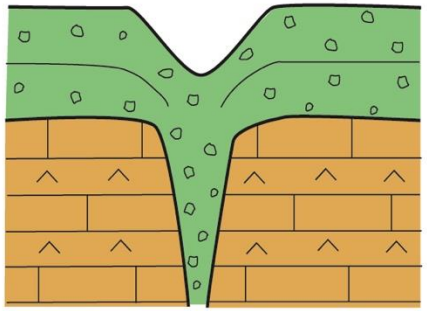
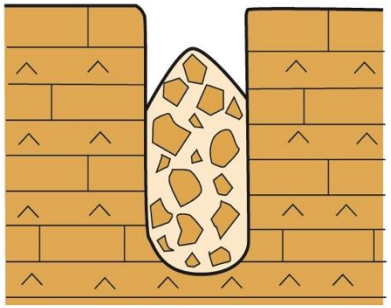
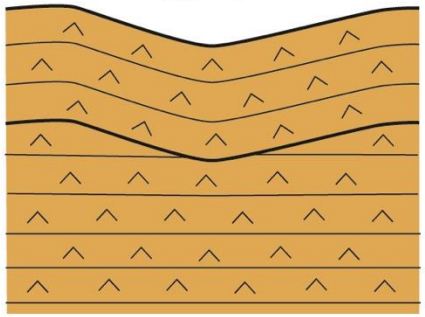
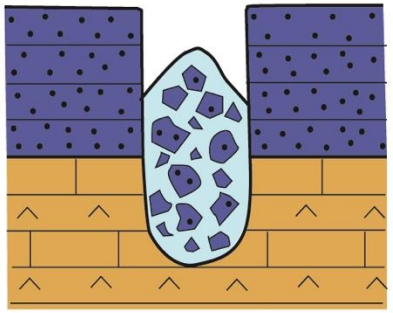
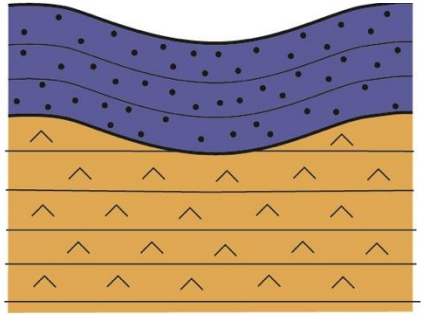
## Mechanical erosion and role of tectonics

1. Water in rapid infiltration into highly porous volcanic deposits (pumice, tuff), highly permeable, and with loose character.

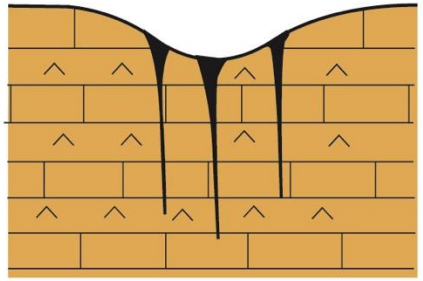
2. Rift faults and fractures act as preferential pathways for water that in depth is able to erode the finer materials (volcanic ashes, silts, sands), progressively removing them and forming underground cavities.

3. Cavities, in time, evolve progressively through failures, until the stage of final collapse is reached, with opening of a sinkhole at the surface.

# SUBSIDENCE SINKHOLES

| | Collapse | Sagging | Suffosion |
|---|---|---|---|
| Cover | Cover collapse sinkhole  | Cover sagging sinkhole  | Cover suffosion sinkhole  |
| Bedrock | Bedrock collapse sinkhole  | Bedrock sagging sinkhole  | |
| Caprock | Caprock collapse sinkhole  | Caprock sagging sinkhole  | |

SOLUTION SINKHOLES



GUTIÉRREZ, PARISE, DE WAELE & JOURDE, 2014, *A review on natural and human-induced geohazards and impacts in karst.* Earth Science Reviews 138, 61-88.


Thanks for your kind attention